

All solid-state high power visible laser

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Final Report: Contract NAS7-1145

Period of Performance: May 22, 1991- May 22, 1993

by William M. Grossman, Principal Investigator

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The overall objective of this Phase II effort was to develop and deliver to NASA a high repetition rate laser-diode-pumped solid-state pulsed laser system with output in the green portion of the spectrum. The laser is for use in data communications, and high efficiency, short pulses, and low timing jitter are important features. Our approach was to develop a short-pulse 1 μm laser oscillator technology, an amplifier to boost the power, and a frequency doubler to take the amplified infrared pulsed laser light into the green. Results are summarized in Table 1 below. The multi-pass amplifiers have both high gains and multi-watts of available power so they are efficient and versatile.

Goals/Results	Goal	Best Result	Deliverable Laser
average power (20 kHz, 532 nm)	2 watts	1.5 watts	1 watt
Pulse Duration (5 to 20 kHz)	< 10 ns	1 ns	1 ns
Beam quality (x diffraction limit)	TEM ₀₀	TEM ₀₀ (1 to 2 x)	TEM ₀₀ (1 to 2 x)
Timing Jitter (% of pulsewidth/ns)	< 10% / 1 ns rms	100% / 1 ns rms	100% / 1 ns rms

Table 1. Results summary.

This summary is Section 1 of this report. Section 2 is an outline, and Section 3 is the history of the program. Section 4 contains Appendices A -C discussing the oscillator and amplifier technology and experimental results. Appendices D and E show part of the Phase III commercialization efforts. Manuals and additional drawings, parts lists, and data describing the deliverable equipment accompany the equipment.

We have moved to commercialize the results of this program; this is "Phase III" commercialization of the technology. We now commercially offer the pulsed sub-nanosecond laser oscillator developed under this contract, and we just commercially introduced the amplifier at the recent (May 1993) CLEO trade show. We applied for a patent on the design concepts of the amplifier, and we submitted journal manuscripts to publicize the short-pulse oscillator and the amplifier results. These have been accepted for publication in *Applied Optics* and *Optics Letters* respectively. We also gave a talk at the 1993 CLEO conference on this amplifier technology. Because the amplifiers are extremely versatile, we are pursuing their use at 1.3 μm for fiber uses under our own funds. We were awarded government funding to extend this program's technology to preamplifiers for communications receivers and to pumping other laser sources.

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3. Program History:

Part A. Progress by 3 month quarters

The following is a history of the program arranged chronologically by quarter-year segments. There are 8 quarter-year segments Q1-Q8 comprising the two-year program.

Q1:

A. Initial directions:

We started by evaluating the status of available technology. After the proposal for Phase II was written, but before the contract started we built a low power 1 μm oscillator that produced <5 ns pulse widths at repetition rates exceeding 20 kHz, a major advance in pulse width reduction. Scaling short resonators to higher powers, however, presents difficulties due to the need to keep the resonator short and the mode large enough to conveniently pump, all in the presence of thermal focusing. We concluded that we could successfully scale to higher powers using an oscillator/amplifier configuration and meet our pulse width goals with a 2 to 10-fold margin. This required new diode-pumped amplifier development and evolutionary oscillator improvements. The advantage of using a short-pulse oscillator approach is that the short pulses increase the peak power and reduce the risk of inefficient second harmonic generation. The remaining risk of using an amplifier is in efficient power amplification.

We performed laboratory tests using available equipment in this first quarter and showed that with Nd:YLF a single point pumped by about 700 mW of diode light in a 200 μm diameter mode can produce about 3 dB of optical gain in a 2-pass arrangement. The experimental arrangement had a pulsed probe beam reflect from an end-pumped Nd:YLF laser crystal.

The oscillators we developed in the year prior to this contract had an average power of about 25 mW, and they needed be amplified over 100-fold (>20 dB saturated optical gain) to the multi watt level to approach the 2-watt design goal. Based on our laboratory results and scaling calculations we felt this scaling was feasible. And after comparing the different possible approaches for efficiently generating several watts of average power in short pulses of green light we committed ourselves to the oscillator/amplifier approach.

B. Oscillator and Amplifier Scaling Needs:

We worked initially in two areas: (1) the design of the oscillator and (2) scaling to high power pumping of amplifiers. We tested the feasibility of coupling a laser diode pump light into and out of fibers. For obtaining higher powers and shorter pulses from miniature low power oscillators we worked with our vendors to explore Q-switch materials that switch larger gains. Our earlier Q-switches were made from fused silica or a special flint glass (SF10). Tellurium dioxide (TeO_2) was a more efficient switch material we had not tried, but it damages more easily than either fused silica or SF10. We then experimentally tested a TeO_2 sample for laser damage, and found it capable of withstanding about 4 J/cm^2 in a 5 ns pulse. The saturation fluence for Nd:YAG or Nd:YLF is well under 1 J/cm^2 , so a TeO_2 switch had good prospects for operating damage-free in a short pulse oscillator. TeO_2 is more acousto-optically efficient than the materials we had used before, SF10 glass and fused silica. TeO_2 is birefringent and must be carefully oriented to allow its use in a polarized laser cavity. We generated detailed engineering drawings of a custom TeO_2 switches and sent them out for bids.

In order to explore generating shorter pulses and producing greater efficiency we also ordered crystals of Nd:YVO₄. This laser material has more gain than Nd:YAG or Nd:YLF, so we felt that in an oscillator it should produce shorter pulses. The Nd:YVO₄ material was a long lead-time item at the start of this contract.

A Spectra Diode Labs 15 watt laser diode bar was ordered and received for use in this contract. We mounted it and characterized its output which matched the SDL data sheet exactly. The diode bar was composed of 35 separate emitting regions, each 1 μm by 100 μm . Our initial design concept for the amplifier was to pump as many as 35 separate points in a laser material with each of the separate emitter regions of the diode bar, and have a laser beam pass through these points sequentially in order to achieve high gain. We knew it was important to keep the pumped area small to retain high gain.

We collected light from the diode bar with a miniature cylindrical lens, sometimes called a fiber lens, in a manner first demonstrated at the Army Night Vision Labs in the early 1970s. The light was then coupled from each of the 35 emitting regions into a 200 μm diameter silica fiber for transport to pump an amplifier. We directed the light from the fiber into a 1.8 mm diameter gradient index lens. After the gradient index lens we measured the transverse beam diameter to be under 175 μm in each dimension measured at 1 mm from the lens. The beam diameter here encloses 80% of the light --scanning a slit from the 10% to the 90% transmitted power points. We collected and measured optical power through a fiber from each of the 35 emitters separately. Summing the power collected from all the emitters we collected 76% of the light through the fibers. This tested geometry had 4 uncoated surfaces, two each on the cylindrical lens and the fiber ends. Coated surfaces might have increased the throughput to near 90%. We measured the positional tolerances for the fiber with respect to the lens in 3 dimensions, and the tolerances of the cylinder lens with respect to the laser diode bar, also in 3 dimensions.

Q2

A. Oscillator technology:

A 200 mW cw laser-diode pumped the oscillator that had emitted ~25 mW of average output power at high repetition rates. This laser oscillator, including the acousto-optic Q-switch was 7.5 mm long, and the permanent fine alignment of the laser parts was done by soldering the components into place. The design of the laser oscillator is shown below in **Fig. 1**.

Diodes with about 500 mW in 50 μm of emitter width became available from Spectra Diode Labs and from Sony Corporation at the start of this Phase II program. These diodes were double the brightness of previously available diodes, and were offered in powers up to 2 watts. We got a sample from Sony of a 50 μm wide diode with 808 nm output that for long-life operation is rated at 400 mW output. We tested the diode for power and stability, and it worked well. By using the 400 mW pumps in our miniature pulsed laser oscillators we produced a 2-fold increase in the output power to over 50 mW average.

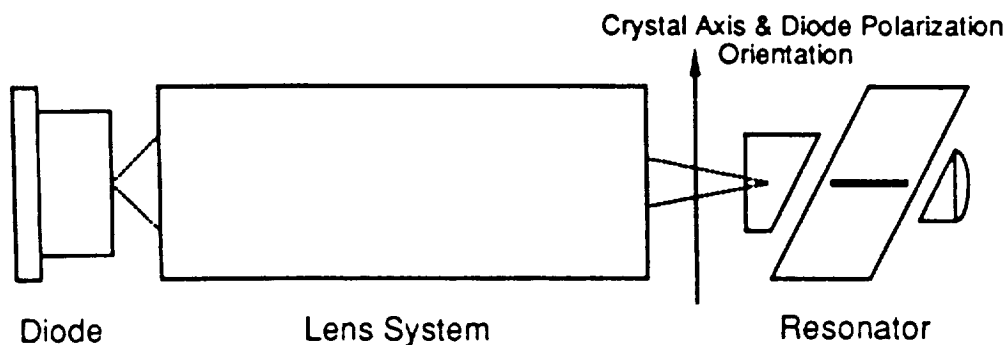


Fig. 1 A laser diode pumps a 3-part pulsed laser resonator, shown on the right. The wedged laser crystal at the left of the resonator is either Nd:YLF or Nd:YVO₄. The middle part with parallel sides is the acousto-optic Q-switch with a transducer located in the center. The optical path through the switch material is about 3 mm long. The third resonator element, at the right, is a partially transmissive output mirror. The 3 cavity elements are separated by air gaps, and the optical path enters each material with low loss from the air at Brewster angle. The length of the resonator is about 7.5 mm.

The inability of the Q-switches to hold off laser oscillation under full pump power had limited the pulse widths of our lasers at low repetition rates. The switch was further challenged as we pushed to higher powers. In addition reduced power consumption at the switch is always desirable. We tested the TeO₂ Q-switches ordered earlier and our results were consistently good. TeO₂ operated damage-free for about 10⁹ pulses in initial tests, and we found no limits on its operating life. TeO₂ worked well at the 1 μm wavelength of interest to this project, and TeO₂ has the added benefit of operating well at the 1.3 μm laser lines of Nd:YLF and Nd:YVO₄ which are of interest for fiber-optic applications. With the TeO₂ Q-switch and a 200 mW laser diode we produced 1.3 ns laser pulses at 1 kHz repetition rates, which we believe were then the shortest pulses from a diode-pumped Q-switched laser.

We conducted our first tests with Nd:YVO₄. We obtained a free sample of Nd:YVO₄ from NEC Corporation in Japan coated for 1.3 μm operation. We ordered Nd:YVO₄ from Litton, Airtron for 1 μm operation. The Nd:YVO₄ needs a 808 nm pump, so we tested the NEC Nd:YVO₄ using our 400 mW double-brightness pump. The results were excellent for producing short-pulse high repetition rate operation. The 1.3 μm pulses were 5 ns at 10 kHz, and under 10 ns at 20 kHz. Typically 1 μm pulses are about 5 times shorter than at 1.3 μm in Nd:YLF, so we became excited about testing the Nd:YVO₄ at 1 μm where to obtain pulsewidths near 1 ns.

Even with the pump power reduced to the levels used with our earlier oscillator work (about 200 mW), at high repetition rates the Nd:YVO₄ gave pulse widths that were nearly half what we typically saw with Nd:YLF. At low repetition rates (~ 1 kHz) the Nd:YLF is approximately equal in pulse width, and superior in power, to the Nd:YVO₄ because Nd:YVO₄ has approximately a 4-fold shorter energy storage time than Nd:YLF. Overall the Nd:YVO₄ allowed us to produce a very short 1 μm master oscillator suited for high repetition rate applications. Nd:YLF also performed well, so we continued testing with Nd:YLF, while further exploring the Nd:YVO₄.

B. Amplifier Design:

In developing an amplification system we examined both multi-pass preamplifiers as well as amplifiers which will only be single or doubly passed. The baseline approach was to amplify the output of a short-pulse oscillator efficiently in a multi-pass preamplifier followed by a straight-through amplifier with 10 to 30 W of pump power. The amplifiers would then be followed by a frequency doubling will then yield at least multi-watt green output. We also decided to test scaling preamplifiers to high enough powers that the straight-through amplifiers would not be needed. Issues were thermal induced beam quality difficulties, parasitic oscillations, and optical damage.

Nd:YLF was our first choice of amplifier material because of its excellent property of having low thermally induced birefringence. However, a Nd:YVO₄ oscillator followed by Nd:YAG amplifier(s) also was considered. We aimed to fiber couple the diode pumps to the amplifying gain medium. We tried to efficiently couple the high power laser diode bars into fibers in a way that we can still pump small (100 μm radius) laser mode diameters in order to achieve high gain.

In the first three months of the project individual emitters from a 35 emitter, 15 W, laser diode bar were coupled to fibers with about 75% total efficiency for diode to laser crystal. We then designed methods to simultaneously grip many fibers. In the following quarter we tested simultaneously coupling groups of 6 emitters into groupings of 6 fibers

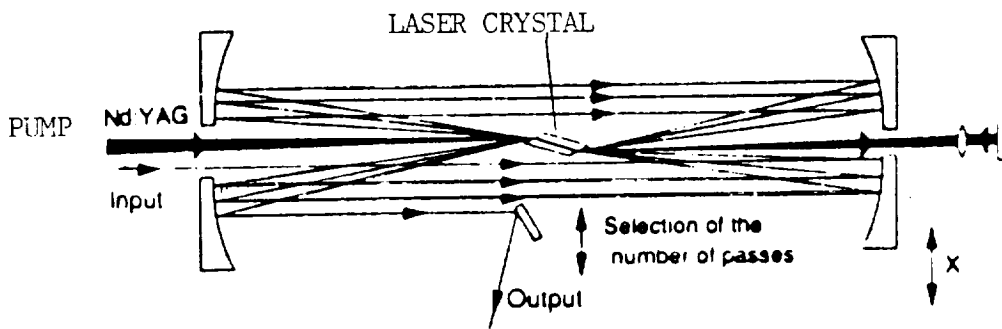
We designed several multi-pass preamplifier concepts. We concentrated on designs that reimaged the beam after each pass through the optical gain medium so that in the presence of thermal lensing the beam size would not grow out of control before any optics could control the beam. We believe this is a difficulty with some optical amplifiers where there are many pumped gain regions that follow each other without any corrective or imaging optics. We conceived and evaluated dozens of design variations. The first amplifier design we felt worthy of testing experimentally was a variation on a confocal multi-pass cavity. Our goal was to find a design that gave good performance without using prohibitively expensive custom optics. In the laboratory we tested a variation of a multi-pass amplifier design known as a "White cell" to get experience with multi-pass amplifier approaches. Our cell was pumped with 1 W of diode power, and was not optimized for more than 4-passes of the gain region. With this amplifier cell we got hands-on experience with a multi-pass amplifier geometry. Care was required to align and to mode-match the

input beam to the cell. Gain and apparent beam distortion were similar to a well optimized double-pass amplifier. It was difficult to achieve many passes and a large optical gain in the tested amplifier cell. Also, the tested amplifier cell required placement of the gain medium at a reflective surface, where thermal lensing from the gain medium is disruptive.

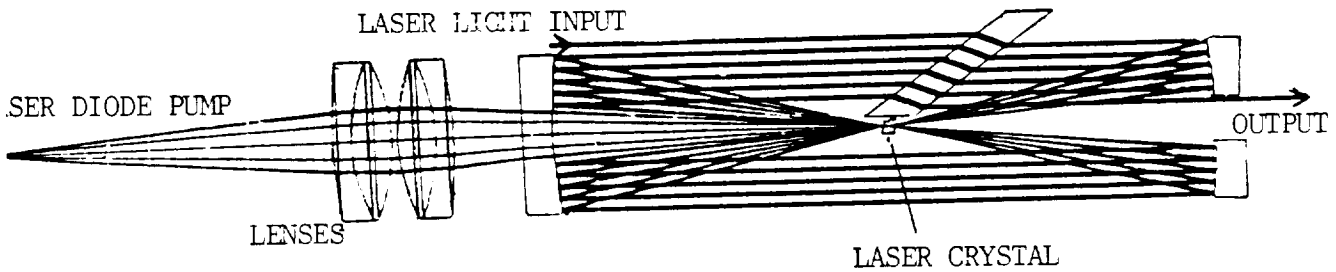
We recognized that a multi-pass reimaging is very desirable such as used by Khoroshilov et. al. (in *Ultrafast Phenomena VI*, Vol. 48 of the Springer Series in Chemical Physics, pp. 21-22 (1988)) or by Georges et. al. (Opt. Lett. **16**, 144 (1991)). The Georges design is shown in **Fig. 2a**: We completed the detailed design of an improved optical preamplifier/amplifier which overcomes some of the problems of non-reimaging amplifiers and improves on several aspects of the Georges design. Our design has many passes through the gain medium, and the gain medium was at a beam waist, so the effects of thermal focusing were minimized, but certainly not eliminated. Unlike earlier designs, our design uses one-to-one reimaging of the beam from pass-to-pass, and the optics were less costly.

Fig. 2a shows the Georges design. The beam path takes a step linearly out of the amplifier after each pass through the Brewster-angled Ti:sapphire gain medium. A doubled YAG laser is the pump. The beam path would not step in a multi-pass sequence if the opposing mirrors were not precisely fabricated of slightly different curvatures. The mirrors have a common focus. A ray passing through the focus is a different distance off the center axis at its intersection with each mirror, because the optical path is longer to one mirror than to the other--the focal lengths differ. Our computer modeling and analysis indicated the mirrors must be parabolas for the needed beam path control. Pairs of custom parabolas with tightly-toleranced and slightly different radii are very expensive (\$10,000 each!). However, some manufacturers make reasonably priced (\$1,000) high quality parabolic mirrors using their standard radii. We realized that if a simple inexpensive Brewster angled glass optical flat is placed in the multi-pass amplifier of **Fig. 2a** then the beam path can be made to walk a multi-pass sequence in the amplifier using two parabolic mirrors, each with the same radius of curvature specification. This design variation is shown in **Fig. 2b**, and includes a single diode-pump and a pair of achromatic lenses for pump collection. Our plan was to test this design and if successful apply more pump power. We ordered the parts to test this design, but the parts were slow to arrive. The key issue for these tests was efficiency and avoiding parasitic oscillations.

As parts for the preamplifier tests are arrived, we tested the diode imaging optics. They worked sufficiently well for the planned proof of principle tests, although not fully optimized for throughput efficiency. We also considered more tidy ways to couple light from the diode bars, but multiple precision aligned fibers appeared to be the best method of routing the light from the diodes to a laser crystal. Pump optics for the next generation preamplifier tests were designed. We chose a simple fiber rod lens to reduce the divergence of the diode light in the rapidly diverging direction (perpendicular to the diode junction). This technique proved very efficient in early tests with an uncoated fiber. Parts were ordered to relay the light collected by the fiber lens into the multi-pass preamplifier/amplifier cavity with a pair of low-aberration achromatic lenses.



2a.



2b.

Fig. 2. (a) Design used by Georges et. al. to multi-pass an amplifier: the two opposing mirrors with holes in their centers are parabolas with slightly differing focal lengths. Our design for a multi-pass laser-diode-pumped amplifier (b) uses a piece of glass with parallel polished surfaces inserted into the collimated beam paths at Brewster angle to displace the beam path so it walks through the amplifier.

C. Frequency doubling to Generate Green Light:

We tested the frequency doubling material LBO. A goal of this program was to produce pulses in the green. LBO worked well. Temperature tuned; it gave up to 45% doubling efficiency in initial testing with 10 kW (50 μ J, 5 ns) peak powers from a diode-pumped Q-switched Nd:YLF laser. The LBO material has been run for about 10^9 shots and shows no sign of degradation. The LBO we used was 10 mm long; 15 mm long pieces of LBO are also available and could further improve the doubling efficiency. We are very encouraged with these results, achieved with about 10 kW peak power.

KTP is another popular doubling material. It didn't work at high doubling efficiency without showing slow degradation. KTP has been the laser community's material of choice for the past several years for use with diode-pumped lasers. One form of optical damage in KTP known as "bulk-darkening" or as "gray tracking" was discussed in the literature (Jacco, Rockafellow, and Teppo, *Opt. Lett.* 16, 1307, (1991)). Heating the KTP slows the damage. However, we observed repeated gray tracking of KTP when a pulsed laser beam is focused into the KTP optimally for second harmonic generation. We tried elevated temperature KTP operation, as well as material from two US vendors (hydrothermal growth and flux growth). Damage is observed in all cases unless the doubling efficiency and power are very low (<6 mW of green light average power). The KTP degradation sequence often has the following pattern: loss of about 25% of the total conversion efficiency due to gray tracking over about the first 10^6 shots, followed by steady operation for about 5×10^8 shots, and finally a second damage stage resulting in the additional loss of about 75% of the remaining conversion efficiency along with beam quality degradation.

We recently obtained a piece of KTP that is the best of about a dozen KTP pieces we have seen at Lightwave Electronics Corporation over the past 3 years. The doubling efficiency slightly exceeds 50% with 50 μ J, 5 ns pulses at 1 μ m incident (10 kW peak power). The KTP exhibits degradation due to gray tracking more slowly than any other KTP tested under similar conditions. However, degradation is observed after two days of use in frequency doubling with pulses incident at 1 kHz. Heating the KTP may improve its damage resistance further. Still, satisfactory long-term high-efficiency operation was never achieved with KTP. We favor LBO over KTP, although KTP continued to improve over the duration of the contract, and is worth further testing in the future.

D. Laser efficiency

The laser efficiency is dominated by the amplifier needed to generate the high output power. An added external factor in the system efficiency that will not be analyzed here is the efficiency of the electronic generation source and the efficiency in tailoring the available voltage to the required levels. The conversion of the electrical power to green light is the product of the efficiency of the sequence of steps required to generate the pulsed green light. The efficiency estimates are presented in Table 2 where the "probable case" is for a laser for use in space with the best available proven current technology; the "best imaginable" uses technology where long life or routine availability may not have been conclusively demonstrated yet. A cost effective first laboratory demonstration was anticipated to have half the "probable" efficiency.

The diode efficiency is a result of the diode's structure, and the numbers given below do not include power consumed in diode cooling. If the diodes require cooling to extend life or select wavelength then cooling effectively reduces the diode's electrical efficiency. We have shown that wavelength selected sets of diodes can be operated on a common heat sink, and therefore may be passively cooled by the ambient environment. In space the diodes could be attached to a radiator in such a way as to require no electrical

power to cool. The "best case" which could be engineered for a space system, is a perfect (1.0) cooling efficiency. In the "probable" case's efficiency estimate cooling is included as is typical of laboratory systems, and this cooling uses as much or more power than the diode requires for optical operation (cooling efficiency 0.3 to 0.5). The efficiency of controls to the laser, operation of the 50 mW average power oscillator, and the Q-switch for the oscillator in the "best case" will add only about 2 W, or in the "probable case" 2.5 W, applied evenly between the Q-switch and the diode in the oscillator. Practical Q-switch drivers can require more power.

The transport of light to the crystal (light to crystal) involves both the capture and movement of the light from the diode through lenses and possibly fibers and into the laser crystal through a coating that may need to reflect the 1 μ m laser light. The quantum efficiency of the crystal is the ratio of the laser photon energy to the pump photon energy, and the branching ratio indicates how many ions reach the excited laser level per absorbed pump photon. Absorptive losses include bulk and coating losses. The doubling efficiency refers to the efficiency of the nonlinear crystal. The efficiency due to unsaturated gain is due to the fact that in a multi-pass amplifier there is a choice between gain and output efficiency:

$$\text{Gain (dB)} / (\text{Small-signal gain} + \text{extracted power}) / (\text{extractable power}) = 1 \quad (\text{Eqn 1})$$

$$\text{Gain (in dB)} = 10\text{Log}(\text{Output/Input}) \quad (\text{Eqn 2})$$

$$\text{Extracted power} = (\text{Output-Input}) \quad (\text{Eqn 3})$$

Thus the small-signal gain is the gain with near zero input and the extractable power is the extracted power with very large input. In this context it is obvious that if we come in with a small input beam and the gain is large then the efficiency is low. The efficiency can be high only if the required gain is low or the available small-signal gain is large, as it can be with multi-pass or multi-stage and multi-pass amplifiers. The best and probable cases can only be realized with a larger oscillator than is presently used and with two stages of high gain amplification. The conservative case can be realized with one multi-pass amplifier.

energy transfer step	best imaginable case	probable case	conservative case
current to light (in diode)	0.5	0.75	0.75
light to crystal (transport)	0.9	0.75	0.60
quantum effcy.	0.76	0.76	0.76
mode overlap (& absorption)	0.90	0.80	0.70
branching effcy.	0.90	0.90	0.90
absorptive loss	0.95	0.90	0.85
unsaturated (due to low input)	0.90	0.80	0.50
doubling effcy	0.8	0.5	0.5
electric to green (net)	0.190	0.048	0.015
diode light (watt) needed per watt green light	2.6	6.8	16.4

Table 2. Laser efficiency (effcy) is the product of the efficiency of each stage in the power transport from electricity to green light. The fractional efficiency estimates in this Table are in the best case for a well optimized system for use in a space application using selected components. A cost effective laboratory demonstration system (probable or conservative cases) will have lower efficiency to save cost in diode wavelength selection and coatings. An fractional efficiency of 0.50 represents a 50% efficient step. The "electric to green" excludes cooling power, the efficiency of the low power oscillator, and of system controls. The controls alone may drop the overall efficiency by another factor of about 0.9. "Best imaginable" and "probable" cases are for systems optimized for efficiency. The "conservative" case is based on what is expected with skilled use of laboratory equipment.

Q3

A. Overview: during the seventh through ninth months of this project we surveyed and tested promising laser amplifier geometries. We also continued to work on improving oscillator performance. The work was divided into the following areas:

- B. fiber-coupled broad-area emitter diode pumped amplifier tests
- C. fiber-coupled diode-bar pumped amplifier tests
- D. single broad-area emitter diode pumped folded-amplifier tests
- E. preparation for a multi-pass amplifier test and oscillator development

B. Fiber-coupled broad-area emitter diode pumped amplifier tests: we coupled 798 nm pump light from a single broad area laser diode into a 200 μm diameter optical fiber and then the fiber emission pumped a Nd:YLF laser crystal. We probed the gain in the Nd:YLF crystal with a cw Nd:YLF laser polarized parallel to the c-axis of the Nd:YLF crystal. We measured the optical power out of the crystal with and without pump power. The gain was 40% per watt of applied pump power over the pump range of 0 to 0.2 watts. This was a good result.

C. fiber-coupled diode-bar pumped amplifier tests: our next step was to fiber couple the pump light from a laser diode bar with multiple emission locations and then pump multiple points in a laser crystal where the pumped points are probed in series by one laser beam. Our 15 W laser diode bar had with 35 emission locations, some slightly stronger than others. Our approach to using the light from this bar was to capture the light in individual fibers aligned to each emitter and use the fibers in groups of 7 to pump separate pieces of Nd:YLF. We tested this idea and found it complex to implement. With a 15 watt bar we collected an average of 0.3 watts into a fiber from each of the 35 emission areas on the diode bar, when collecting light from each emission area, one at a time. We built a holder to position fibers on evenly spaced centers so that multiple fibers are simultaneously aligned in front of the diode bar using a single alignment fixture. This structure is shown in **Fig. 1**, and it worked well.. With 7 fibers in the holder we collected about 3 watts of diode light through the fibers and onto a detector. To do this we were obviously aligned to some of the stronger emitters. Otherwise we could not have coupled 3 watts, 20% of the 15 W of available light, from 20% of the bar's emitters--which is perfect coupling and impossible. The overlap of the pumped volumes and the probe beam is critical, and the pumps are under 200 μm in diameter; consequently, the overall alignment of the probe and pump beams was difficult. If we could align these pumps to serially amplify a probe beam then the gain would be 12% per point with 300 mW of pump per point, and the 7 fiber pump points would give a gain of 121% ($1.12^7 - 1$) or 3.4 dB. Then 5 sets of 7 fibers (coupling the full 35 emitters from the bar) would give 17 dB gain, or a gain of over 50x. This is an attractive gain, and shows the 40%/watt gain is useful. However, we were not able to realize all of this gain due mainly to misalignments.



Fig. 3 A holder to position fibers on evenly spaced centers so that multiple fibers can be simultaneously aligned in front of the diode bar using a single alignment fixture. The 35 emitter laser diode bar is the gold structure in the right center. The emitters on the diode bar are each 100 μm wide and are located on 280 μm centers. A pair of copper guides with grooves cut on 560 μm centers are used to hold reference fibers that then grip the optical fibers. The copper guides clamp together to position and hold the optical fibers, and are located in the middle of the picture. A Plexiglas housing purged with dry air keeps condensation and icing from forming on the diode. The diode is mounted on a metal base which is in turn mounted on a pair of thermoelectric coolers that control the diode temperature and wavelength. This picture is approximately full scale.

We soldered an array of 7 lenses into an aligned group and used this group to image pump light from 7 fibers held in a set of mechanical channels. The source of the light is the laser diode bar shown in **Fig. 3**. The light imaged by the array of 7 lenses pumps a Nd:YLF bar-shaped crystal, as shown in **Fig. 4**. The crystal is pink in color and is located between the silver colored clamp holding the fibers and lens and the white mirror sitting atop an aluminum support. The bar is multiply-passed by a probe laser beam from a Nd:YLF laser (not shown). It is difficult to align the small pump beams to overlap the probe beam within the Nd:YLF and we observed nowhere near the predicted gain from 7 pump points. The gain measured about 26% from the 7 pump points, where theoretically we could have produced 121%. This concept with a 35 emitter bar should provide reasonable amplification, but the attention required for alignment made the concept undesirable and we abandoned it at that point for other options.

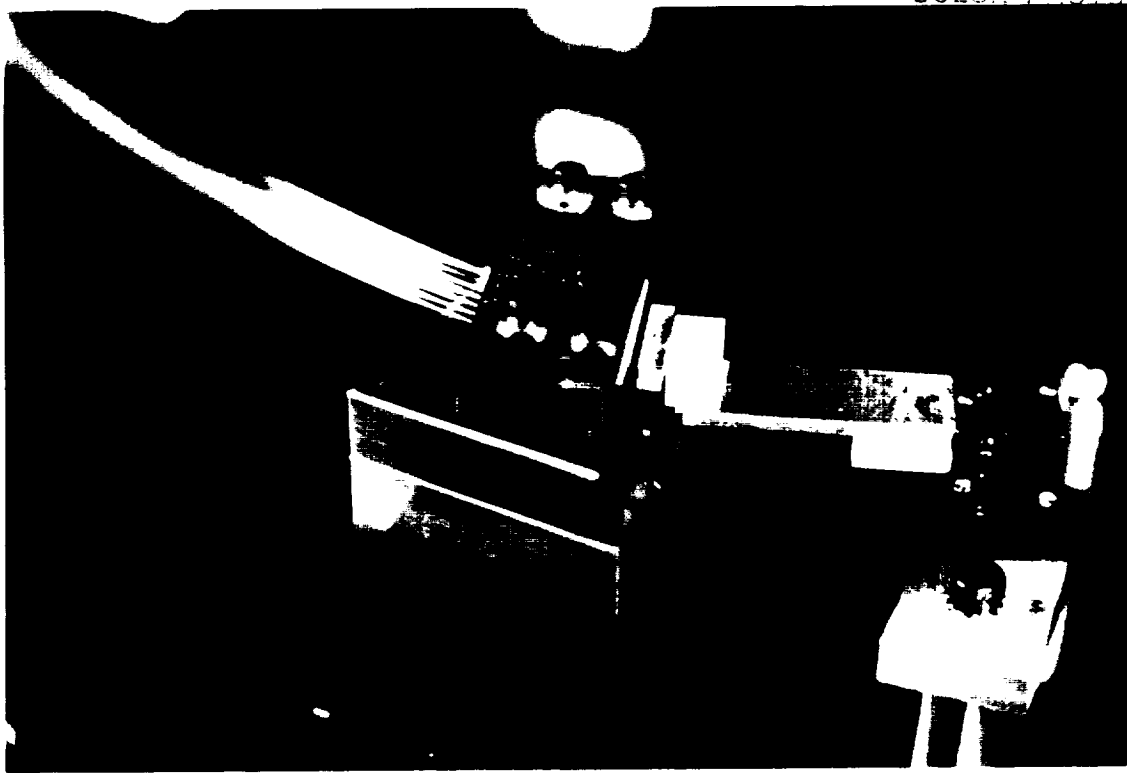


Fig. 4. The metal structure guides an array of 7 fibers carrying diode pump light into a soldered array of 7 lenses. The light imaged by these lenses pumps a 3 mm by 3 mm by 14 mm Nd:YLF crystal to the right of the fibers, and the Nd:YLF is multiply-passed by a probe laser beam from a Nd:YLF laser (not shown). The light crosses through the Nd:YLF, reflecting 7 times from an external mirror to the right of the Nd:YLF. The mirror almost touches the Nd:YLF. After each reflection from the left surface of the Nd:YLF the probe light is further reflected back toward the external mirror by a coating on the left-facing surface of the Nd:YLF.

D. single broad-area-emitter diode-pumped folded-amplifier tests:

We next examined a simpler geometry shown in **Figs. 3 and 4** to multi-pass a single pump-point. This idea, suggested by Tom Kane, used 2 flat mirrored surfaces with a gain medium located between them. The surfaces were slightly angled so that a beam between the two multiply reflected from the mirror pair and passed through a selected gain region several times. The figures exaggerate the angle between the mirrors, and in practice we had one of the reflective surfaces coated onto the Nd:YLF itself as shown in **Fig. 6**, and the other reflective surface on an independent mirror. The pumped region was the small volume where the beams overlap, at left in the figures. A photograph of the experimental arrangement is shown in **Fig. 7**. The diode in a package is at right. A series of lenses image the diode light into a 3 mm by 3 mm by 14 mm Nd:YLF crystal that is suspended and heat-sunk by a copper holder at in the left-center of the picture. The right hand 3 by 14 mm face of the Nd:YLF is highly reflective at $1\ \mu\text{m}$ and highly transmissive to the $0.8\ \mu\text{m}$ diode light. Directly to the left of the copper block and the Nd:YLF is a mirror that forms the second reflective surface (as shown in **Fig. 5**) in the amplifier. The mirror is mounted with angular adjustment. The two surfaces that are reflective to $1\ \mu\text{m}$ light are intentionally aligned so they are about 1 degree off of parallel.

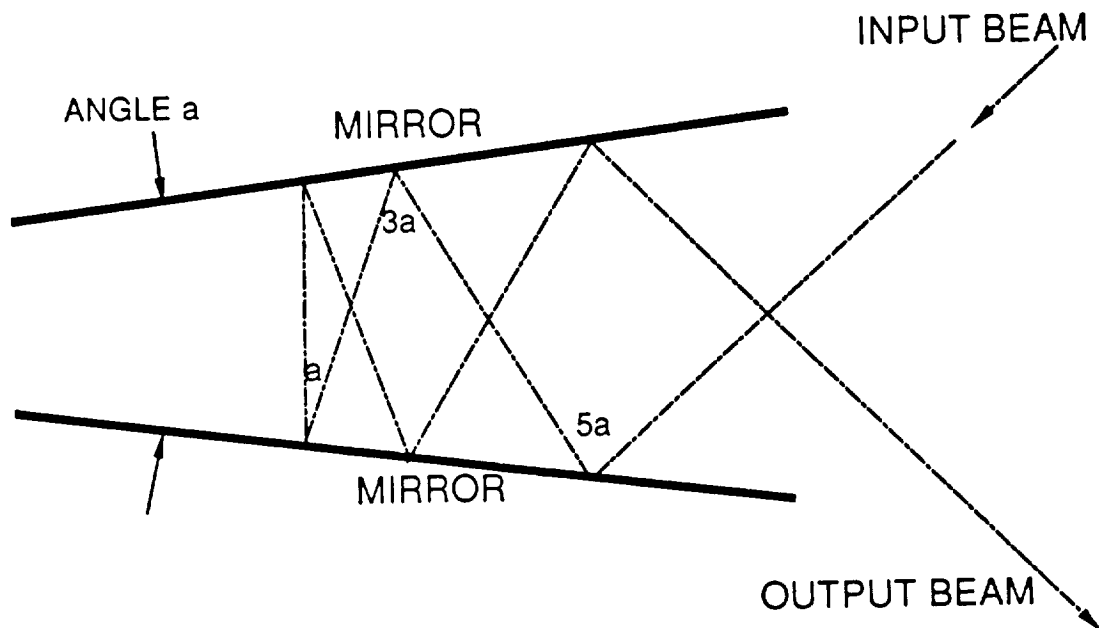


Fig. 5. Concept for a simple multi-pass cell in which a diode-pumped gain medium can be situated. The laser material would be located between the mirrors.

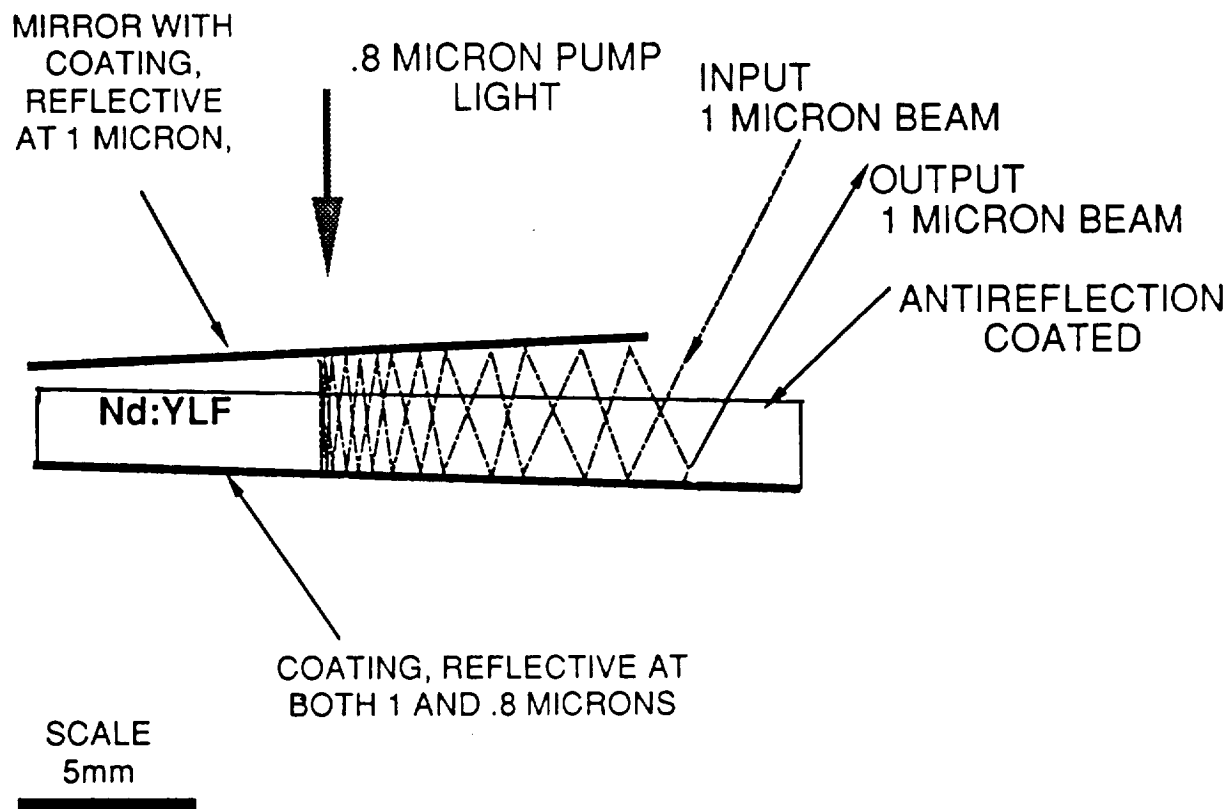


Fig. 6. Concept for a multi-passing of a Nd:YLF part with pumping at the area where the probe beam is tightly overlapping. The beam will pass through the pumped portion of the gain medium about 6 times if the angle between the mirrors is about 1 degree.



Fig 7. The diode (at right) followed by series of lenses pumps a 3 mm by 3 mm by 14 mm Nd:YLF crystal suspended and heat-sunk by a copper holder at left. The right hand 3 by 14 mm face of the Nd:YLF and a mirror farther to the left form the 2 reflective surfaces needed to multiply reflect a probe beam into and out of the pumped region in the Nd:YLF.

E. Preparation for a multi-pass amplifier test and oscillator development. Preparation continued for a multi-pass amplifier test using two confocal opposing mirrors of slightly different curvatures (the mirrors have a common focus) with tests of some of the diode imaging optics. These tests occurred prior to the arrival of the parabolic mirrors which were a half-year to arrive coated! About the time of the arrival of the parabolic mirrors we also received fabricated 1.064 μm coated Nd:YVO₄ crystals and we concurrently prepared to test miniature 7.5 mm cavity length pulsed oscillators using this material at repetition rates up to 100 kHz. The laser used 400 mW laser diode pumps and we built two pulsed oscillators, one of Nd:YVO₄ and one of Nd:YLF for use in this program.

Q4

A. Overview: During this period we demonstrated a sub-nanosecond miniature pulsed laser oscillator, and we tested our multi-pass confocally reimagining amplifier with this oscillator. This is the amplifier that is the basis for the bulk of the high power work that follows. The amplifier results are with 1.6 W of absorbed pump light. The amplifier produces over 0.6 W output with 0.04 W input, and has 38 dB (a factor of 6000) small-signal gain. The work was divided into the following areas:

- B. short-pulse oscillator development
- C. multi-pass amplifier tests

B. short-pulse oscillator development

We demonstrated a miniature 1.064 μm Nd:YVO₄ pulsed oscillator with a 7.5 mm cavity length including the Q-switch. We used one 400 mW laser diode to pump the Nd:YVO₄ and pulsed this Nd:YVO₄ laser at repetition rates of 1 to 100 kHz. We built up two pulsed oscillators into soldered and packaged units for use in this program, one of Nd:YVO₄ and one of Nd:YLF. The Nd:YLF laser has low repetition rate (1 kHz) pulses of 800 to 900 picoseconds and the pulse width grows at higher repetition rates. The Nd:YVO₄ also has low repetition rate (1 kHz) pulse widths of 800 to 900 picoseconds, and at 100 kHz the laser still has about 1/2 μJ of energy per pulse and a 2.1 ns pulse width. The short-pulse high repetition-rate performance was a success.

We have observed that the beam has some scattered light causing an imperfect transverse profile that might require filtering prior to amplification. Also after some pulses there is a small amount of trailing power which is due to the shut-off speed of the Q-switch. Maximizing the output coupling of these lasers increases the pulse buildup time and reduces the laser's sensitivity to the switch shut-off speed. These oscillators are breakthroughs in diode-pumped laser technology, and we moved to commercialize them in the spirit of this SBIR development program. There were no commercially available Q-switched lasers with sub-nanosecond pulse widths, and there is a small demand for this type of laser for characterizing and testing photodetectors and for laser ranging applications.

The laser oscillator is packaged in a hermetically sealed container which is mounted in a case that carries the oscillator, the radio-frequency drive electronics to power the Q-switch, and the DC drive electronics that power the laser diode and temperature controls. The laser in its case can be seen on the left side of the photographs, **Figs. 8 and 9**. The package is gray and sits on a gold colored mounting base. In the photographs the base is bolted to an aluminum pedestal that is not part of the laser. The laser in its case measures approximately 8 by 10 by 15 cm.

C. multi-pass amplifier tests

The amplifier concept with two confocal opposing parabolic mirrors was tested. The probe beam sent into the amplifier is from the short-pulse Nd:YLF oscillator described above. **Figs. 8 and 9** show two views of the bench-top amplifier experiment. The tests are done on optical breadboards with tap-holes located on 1" centers; this sets the scale in the photographs. In **Fig. 8** the laser diode is located in a purged pink plastic enclosure at right that is attached to a heat sink. The enclosure contains a dry-gas purge to prevent condensation and icing on the cooled laser diode. A fiber lens that collects the diode light is in front of the laser diode, held by an aluminum arm. A pair of achromatic lenses held in black mounts relay the diode light to the laser crystal in the amplifier. The lenses are about 12.5 cm from the diode and are 50 mm in diameter. A black Allen wrench ball driver appears to point to the bottom of one of the lens mounts, and the second lens is hidden by its mount directly to the left.

The amplifier itself has four main elements, two mirrors surrounding a laser crystal, the laser crystal, and an angled piece of glass that makes the beam under amplification step in a multiple-pass path through the oscillator. The beam path is shown in **Fig. 9** on the drawing on the white paper behind and above the amplifier. The drawing is full scale compared to the parts. The crystal is in the aluminum assembly near the center of **Fig. 9**. The assembly has a 5 by 5 cm footprint, and about 8 cm high. It is a sandwich with the 0.3 by 0.3 by 0.5 cm Nd:YLF in the center, out of view. Above and below the crystal are heat spreaders, each linked to a thermoelectric cooler that is heat sunk in a water cooled plate. The red and black wires attached to this assembly are for the thermoelectric coolers. The water is not attached in the photographs, but is available if needed as we scale to higher powers. The two mirrors that route the laser light through the amplifier are best seen in **Fig. 9**. They each have a 5 cm diameter. The one at left next to the gray oscillator has a small (~1 cm) hole in it that admits the input beam from the oscillator. The other mirror is symmetrically placed about the aluminum structure and is adjacent to the mounts that hold the achromatic lenses. The angled piece of glass that steps the beam through the amplifier is evident emerging from the aluminum structure that contains the Nd:YLF, and the glass is oriented pointing toward the oscillator.

The probe beam passes through the gain medium typically 12 times. When the Nd:YLF crystal in the center of the amplifier is pumped using about 1.6 W of incident pump power the multi-pass small-signal gain was 38 dB, a factor of 6000. To observe this small-signal gain we probed the amplifier with an average power of about 1 μ W. With cw input of 40 mW the output was .64 W, and with high repetition rate pulsed input of about 25 mW the output was about half a watt. The optical to optical efficiency is typically 30% to 35% based on incident pump power. The amplifier did not change the pulse width of pulses under amplification. The amplifier did preferentially amplify the leading edge of the pulses, so that the timing of the pulses advanced by about 1 ns when the amplifier is pumped. The confocal design of the amplifier places a beam waist in the gain region. The spatial profile of the amplified beam appears round and Gaussian, as measured using a beam scanning profile measurement system. The beam passing through the amplifier cell when the pump light is blocked is not nearly so symmetric, and the repeated filtering by the small gain region at the beam waist may account for the excellent beam quality. The amplifier is as efficient as an oscillator. Our goal was to scale the amplifier to higher power.

On another program we are prepared a pump module suitable for pumping Nd:YAG or Nd:YLF with >10 W in a 400 μ m diameter mode. To minimize technical risk, we planed to use this source for our high-power amplifier tests prior to committing to buy a pump module for this NASA program. The source is a 400 μ m core diameter fiber carrying the collected light from five separate 3 W laser diodes.

We have designed and built a holder for mounting a laser crystal in the amplifier that can dissipate greater heat for use with the new ≥ 10 watt source. For the higher power tests we are shifted to Nd:YAG from Nd:YLF because Nd:YLF usually breaks when pumped with 10 W in a small mode. We had, however, examined the possibility of obtaining more rugged Nd:YLF that could be fabricated by etching to relieve surface strain and microcracks that usually contribute to thermally induced surface fracture. Etching is believed to double the power-induced fracture limit in Nd:YLF. Fabricated, polished, etched, and coated material is available from Coherent Inc. Optics Group in Auburn CA, but the cost is high, about \$10,000 for a lot of 1 to 5 parts. We decided to bypass this high risk and potentially slow process of using Nd:YLF and proceed with using Nd:YAG.



Figure 8. Photograph of the oscillator-amplifier breadboard experiment. The oscillator is completely self-contained including electronics in the packaged gray case at left with the Lightwave logo on the side. A pump diode for the amplifier is in the pink enclosure at right. The Nd:YLF amplifier crystal is in the aluminum block-like cooling structure in the middle. A 5 cm diameter pair of mirrors surround the Nd:YLF and are the primary beam steering mirrors through this multi-pass amplifier.

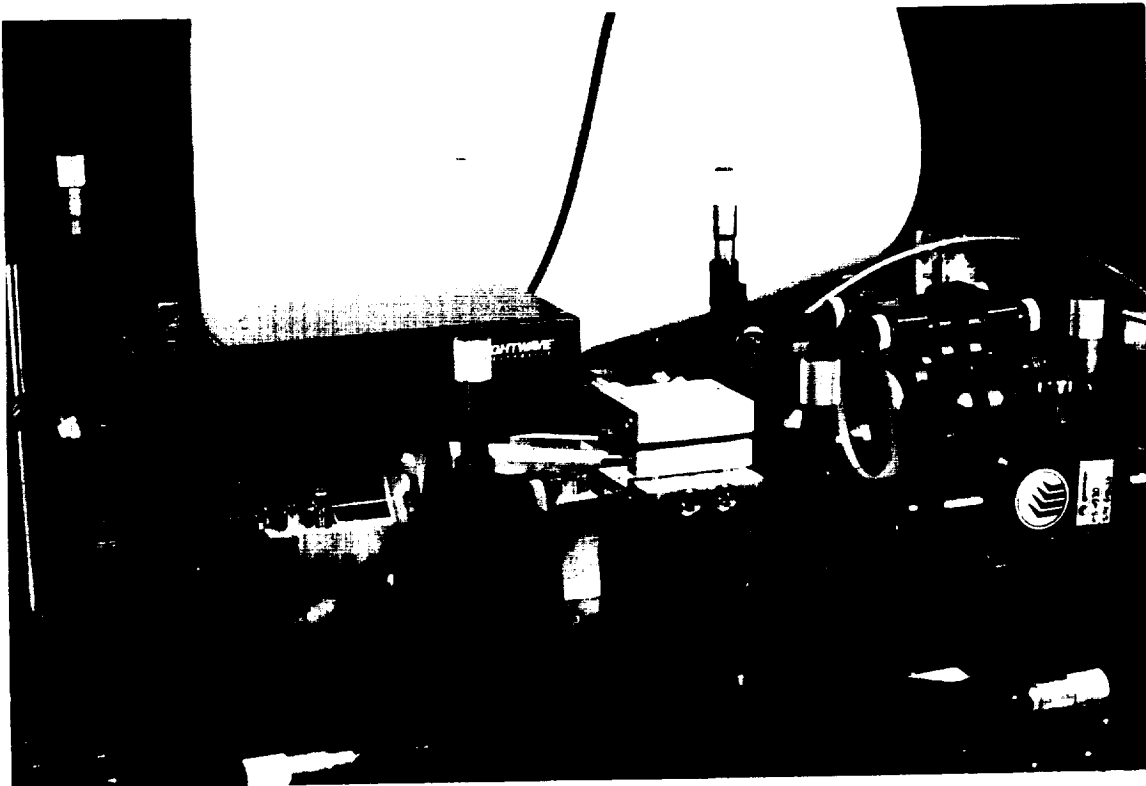


Figure 9. Second photograph of the oscillator-amplifier breadboard experiment. The layout is the same as in Fig. 1. The white drawing in the background shows a full-scale drawing of the beam path.

Q5

A High-power fiber-coupled diode pump source

We built a pump module for this program suitable for pumping Nd:YAG or Nd:YVO₄ with about 11 watts of 808 nm laser diode light from a 400 μ m diameter fiber. The fiber emitted with a numerical aperture (NA) of 0.33, and was later upgraded to NA of 0.25. The pump module used five 3 watt diodes, four of which were then good diodes, and the fifth was a manufacturer supplied reject which provided about 1/3 rated power and was due to be replaced.. Under this contract we assembled the five diodes into a fiber-coupled module.

B. Multi-pass amplifier scaling tests

The amplifier concept using two opposing confocal parabolic mirrors was tested with the new fiber-coupled pump module. The 1.06 μ m sources that were amplified included both a CW Nd:YAG laser and a pulsed Nd:YVO₄ laser. We also used Nd:YAG and Nd:YVO₄ as the amplifying medium. Our results indicated an excellent wavelength match between Nd:YAG and Nd:YVO₄, making them interchangeable. Nd:YAG and Nd:YVO₄ also use the same pump wavelength. In all cases the Nd:YVO₄ gave more gain and output power from the amplifier than Nd:YAG. We achieved nearly 3 W of single-frequency light from the amplifier with about 0.5 W of CW single-frequency input. With pulsed input of about 50 mW we obtained over 1.5 W of pulsed power at repetition rates of 20 kHz and above. The pulse widths at 20 kHz are under 2 ns, and the peak powers approach 50 kW. Some results are summarized in Table 3 below:

	Nd:YAG amp output	Nd:YVO ₄ amp output
CW Nd:YAG oscillator (500 mW input to amp)	1.5 W	2.8 W
CW Nd:YAG oscillator (30 mW input to amp)	0.36W	not yet measured
Pulsed Nd:YVO ₄ oscillator (35 mW to amp, 20 kHz)	not yet measured	1.55 W

Table 3. Amplifier results are total output power. The results were with the amplifier crystal's heat-sink cooled about 35 °C below ambient, except the CW Nd:YAG oscillator/Nd:YAG amplifier result where the amplifier crystal's heat-sink is at ambient temperature. In all tested cases cooling improved performance.

In other experimental results at Lightwave we had seen doubling efficiency between 50% and 70% with LBO, so we planned to use LBO to double the amplified laser output. To increase the power out of the amplifier we extrapolated that increasing the amplifier output will require more pump power and more efficient collection of the pump light. Although the fiber source emits over 10 W, only about 6 W are incident on the amplifier crystal due to constraints on the pump light imaging optics due to the wide divergence from the fiber and losses at the pump optic coatings. With the reject fifth diode in the fiber module replaced with a good diode and with the pump optics optimized we calculated we would be able to obtain 50 to 75% more pump light at the crystal.

Summary of other results:

- Output beam profile: matched input profile of seed source--TEM₀₀.
- Pump beam profile out of fiber: approximately uniform flat-top.
- Thermal lensing in YAG was observed; plano-concave lenses at the YAG were tested and successfully compensate thermal lensing.
- Thermal lensing from Nd:YVO₄ is qualitatively similar to that from Nd:YAG
- The same pump and Nd:YAG produced ≥3.6 watts of TEM₀₀ from a simple resonator, but contributes a net 1.5 watts in the amplifier, so extractable power was available.

The amplifier extraction efficiency was good (~40%) based on power incident on the Nd:YVO₄ in the CW case with a large oscillator. With slightly greater pump power we calculated that the amplifier would move farther into saturation with the pulsed input, and efficiency there would further improve. If the small-signal gain is too high and we have excess gain we could have undesirable amplified spontaneous emission; however, it is easy to reduce the gain by reducing the number of passes through the amplifier.

The plans at this stage of the program were to do the following tasks (A-J) quickly.

- A. Test doubling efficiency
- B. Improve pump optics
- C. Improve pump power
- D. Model Gaussian beam in amp
- E. Measure small-signal gain
- F. Test YLF in amp
- G. Further study compensating thermal effects
- H. Fine tune YVO₄ oscillator
- I. Test YVO₄ in a stand-alone oscillator to access available power
- J. Test YVO₄ amplifier with a larger oscillator

The program status at this time was as follows:

- A. Technical:
 - a. oscillator pulses were short with both YVO₄ & YLF.
 - b. LBO doubles pulses well and we had ordered LBO.
 - c. Small signal gain of YLF: 38 dB with 2 W pump, 200 μm mode.
 - d. 1.6 W incident on YLF adds 600 mW to seed beam.
 - e. YAG small signal gain: 14 dB for ~5 W pump, 400 μm. mode.
 - f. Thermal lensing in YAG corrected by negative lenses.
 - g. No obvious birefringence problems with YAG.
 - h. Insertion loss about 1% per pass through gain medium.
 - i. YVO₄ didn't break with 10 W pump, so pumped by fiber module and it worked great.

- .b. Pump module upgraded to increase power from 10 to 11 W and reduced NA from 0.33 to 0.25..
- c. With new module: pumped YAG & YLF
- d. Need to model amplifier with thermal lens with Gaussian beam optics.
- e. Pump transmission in lenses & mirrors = 80%; also losses going into lens due to lens NA reduces pump power another 20%. In an oscillator configuration we found we can capture substantially more of the light using mirrors. We ordered mirrors for use with the amplifier. We need to test these when they arrive.
- C. Risks at that time were:
 - a. If not enough gain in YAG for goals with even 15 W pump.
 - b. Thermal effects. could complicate--force using a chain of amps.
- D. Other topics:
 - a. (to reduce risks "a" and "b" above) Bought seven 807 nm C-mount 3-watt diodes ~\$20k. Test YAG pumping with other pump geometries. Also a backup if module died. These diodes eventually shipped in deliverable.
 - b. (to reduce risks "c" above) Tested YVO₄ oscillator & YAG amp; they worked very well together.
 - c. d. Tried side-pumping YLF in a non-amplifier test with a 15 W bar. It worked very badly; extracted only ~0.3 W.

Q6

A. Multi-pass amplifier scaling tests

The amplifier concept using two opposing confocal parabolic mirrors was tested with the new fiber-coupled pump module. The 1.06 μm sources that were amplified included both a CW Nd:YAG laser and a pulsed Nd:YVO₄ laser. We also used Nd:YAG and Nd:YVO₄ as the amplifying medium. Our results indicated an excellent wavelength match between Nd:YAG and Nd:YVO₄, making them interchangeable. Nd:YAG and Nd:YVO₄ also use the same pump wavelength. In all cases the Nd:YVO₄ gave more gain and output power from the amplifier than Nd:YAG. We achieved nearly 3 W of single-frequency light from the amplifier with about 0.5 W of CW single-frequency input. With pulsed input of about 50 mW we obtained over 1.5 W of pulsed power at repetition rates of 20 kHz and above. The pulse widths at 20 kHz are under 2 ns, and the peak powers approach 50 kW. Some results were summarized in Table 4 below:

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Table 4. Amplifier results are total output power. The results are with the amplifier crystal's heat-sink cooled about 35 °C below ambient, except the CW Nd:YAG oscillator/Nd:YAG amplifier result where the amplifier crystal's heat-sink is at ambient temperature. In all tested cases cooling improved performance.

The results of summary for this stage of the program was:

A. Test doubling efficiency:	result: $\geq 66\%$ efficiency
B. Improve pump optics:	status: improved power delivery by $\sim 40\%$
C. Improve pump power:	status: finished 6-diode pump modules
D. Model Gaussian beam in amp:	status: done--understand thermal effects
E. Measure small-signal gain:	result: ~ 37 dB with YVO ₄
F. Test YLF in amp :	result: Nd:YLF inferior to Nd:YVO ₄
G. Study thermal compensation:	result: Nd:YVO ₄ needs 3x more than Nd:YAG
H. Fine tune YVO ₄ oscillator	result: performance vs. rep. rate improved
I. Test YVO ₄ in big oscillator	status: got 4 W out with ~ 10 W pump
J. Test YVO ₄ amp & large oscillator	status: on hold; small oscillator working

We then replaced the reject fifth diode in the fiber module with a good diode so the module produced about 15% more power, and with the alignment of the pump module was optimized so it emitted 50% more power than before into a low divergence ($N.A. \leq 0.2$). We tested reflective pump optics and achieved about 10 W of pump light incident on the amplifier crystal. Pumping Nd:YVO₄ in the amplifier gave about 3 W of amplified light with a CW input, but thermal lensing makes the beam an elliptical, but still a correctable, TEM₀₀ mode. A slightly higher power and lower numerical aperture pair of polarization coupled pump modules was built that gave about 13 W of pump light. We tested the generation of green light with this increased power pump, and we generated an average power of 1.5 W of green light at the project's design pulse repetition rate of 20 kHz.

At a 20 kHz pulse repetition rate the pulse width is well under 2 ns. The pulsed output of the amplifier was frequency doubled to the green using the material LBO. The short pulses resulted in peak powers of about 50 to 75 kilowatts, and the doubling efficiency was consequently high. We obtained doubling efficiencies of up to 66% with Type I noncritically phase matched temperature-tuned LBO. Critically phase matched Type II LBO gave about 50% conversion efficiency. We produced the 1.50 watt of pulsed green light described above with Type I LBO.

With Nd:YAG as the amplifying medium we achieved an average pulsed power of 2 to 2.4 W, and with about 3-fold less thermal lensing compared with Nd:YVO₄. Doubling this to the green gave about 1.25 watt of average power. The amplifier design has good efficiency, and the extraction efficiency is relatively insensitive to thermal focusing, but it was still desirable to compensate for some of the thermal focusing to keep the beam size controlled outside of the gain medium.

We finalized our design definition in several areas, and were now changing from an exploratory experimental phase of the program to design of the deliverable system. Our design definition was as summarized below. The diode module was chosen to be fiber coupled to the amplifier. The oscillator is called a "model 111V"; and is the custom designed short-pulse Nd:YVO₄ oscillator built and presently in use for this program. We had made a "mechanical plan drawing" of the laser system indicating key parts, degrees of freedom on the mount for each key part, and the range of motion and type of

adjustment (if any) for each part. A second "electrical plan drawing" of the location and controls for all electrical features was generated.

¹B. Risks:

Three months earlier we had listed the risks as follows:

- a. If pump module is delayed.
- b. If not enough gain in YAG for goals with even 15 W pump.
- c. If YAG amp and YVO₄ osc. don't work well together.
- d. Thermal effects. Could complicate--force using a chain of amps.

At this point we had the pump module and it was working well. Thermal effects were complicating our efforts, and we were having YAG and YVO₄ parts fabricated with concave surfaces to compensate the lensing in these materials. Our plan was to build the deliverable system and test it without delay, expecting to overcome difficulties as they arose. An area we anticipated requiring particular care was controlling the peak and average powers on the gain and doubling elements to prevent optical and thermal damage.

C. Design Definition DRAFT:

A. Technical Approach:

Multi-pass confocal design
Diodes: JPL unit has multi-diode modules
JPL system architecture: (1) electronics drive with diode module, (2) oscillator, and (3) amp head. Connections are electronics umbilical & fiber-optics.
Cooling: to air cooled heat sinks preferable
Laser material: Nd:YAG amp, and Nd:YVO₄ oscillator.

B. Product Performance Specifications:

Performance:

Small-signal gain: 40 dB typical.
1.064 μm pulsed and externally doubled to 0.532 μm .
Average power: 1.5 watts at 0.532 typical,
: ≥ 2.0 watts goal at 20 kHz repetition rate
Polarized.
TEM₀₀ (goal: round within 10% at 1/e²).
Output beam diameter/divergence; probable 350 μm , 4 mr @ 1 μm
75 μm , ~10 mr @ 0.5 μm .
Waist location along optical path: probably centered in amplifier.
Pointing stability, waist location & far-field angle: goal within 10% of diameter & divergence/yr.
Astigmatism: goal <10% z_R after correction optics if needed.
Warm-up: determined by rate doubler can reach temperature

C. External Design Definition:

Inputs: Model 111V custom 20 kHz short-pulse oscillator
(for tests during building also a CW single-frequency ring laser--

standard Lightwave model 122)
Outputs: pulsed IR or pulsed green set at factory
Indicators: CDRH warning light
Standards goal: FCC, VDE, CDRH, UL certifiable (not certified)
Shutter: required, manual operation.
Size/Weight: to be determined.
Cooling: See Internal specs.

Amp & controls units:

Separate detachable units--head and control electronics are modular,
separated by cable of length ~ 2 meters.

Electrical Power:

AC 110 volts, 60 Hz

Power dissipation: goal is to minimize dissipation, probable maximums.

At amplifier head: ≤ 150 W

At diode module: ≤ 350 W

At control electronics: ≤ 700 W

D. Internal Design Definition:

Diode Pump: JPL module type will be a multi-diode module, fiber coupled into a single fiber. The light will be coupled into the multi-pass cavity by a split mirror with a 90 degree bend created by a 45 degree mirror. The diodes will be electrically in series within the module. The coolers for the group of diodes will be 4 TECs, each 6 amp, 12 volts in a parallel-series arrangement.

Diode current maximum: probable max: 7 amps, 15 v per module
Diode current allows 25% increase of initial (not exceeding max stated above).

Cooling: Control electronics--air
Diode module-- air (or self-contained water-to-air system if needed).

Head-- Air or conduction to user's heat sink or water--if needed; Crystal TEC maximum: probable max. 6 amps, 24 v

Isolator (input): included between Model 111V and amp.

Isolator (output): as required; leave space but do not put isolator into prototype.

Frequency doubling: LBO temp. stable at $\sim 150^{\circ}\text{C} \pm .25^{\circ}\text{C}$.

Double oven: control electronics adapted from other Lightwave projects

Laser Crystal: Nd:YAG, (backup alternative Nd:YVO₄) temperature stabilized $\pm 1^{\circ}\text{C}$
cooled $\sim 0^{\circ}\text{C}$.
Twin 6 amp, 12 volt TECs in series

Interlocks: CDRH required, short and open safe desired on all head connections

Safety: Manual shutter, yellow lights, remote interlock connector

D. Transition to Phase III: We were working on plans for Phase III commercialization. The short-pulse Nd:YVO₄ oscillator technology that was developed as part of this program was already in Phase III, and was commercially available. We were then defining markets where the amplifier technology of this project is applicable. We initiated a project internally to test applications of the amplifier for a commercially significant communications area where we are familiar with the markets. As part of the Phase III effort we publicized the results of this present NASA-supported work. We submitted a manuscript which went to *Applied Optics* on the short-pulse oscillator work supported by this program. We submitted an abstract to the 1993 CLEO conference for a talk on the amplifier results. Prior to that submission we submitted a patent application for the amplifier design. A copy of the *Optics Letters* and the CLEO submissions are included as appendices X and Y of this report. Information on a patent application has been transmitted to NASA in compliance with the requirements of this contract. The abstract of the patent application is included with this report as appendices Z.

Q7

A. We tested a folded version of the amplifier with bare optics that are about 10 cm long instead of 20 cm long for the amplifier design that we have tested extensively that uses twin

parabolic optics. Our initial results with the folded version used Nd:YAG, and we produced optical efficiencies of about 25% based on pump light converted into 1 μm light. These results were encouraging, but we had not tested the folded amplifier sufficiently in direct comparison to the twin-parabolic design to for optical efficiency or for maintaining polarization. Maintaining polarization was important for efficient second harmonic generation. It appeared that the folded design could reduce the amplifier length and volume. For these reasons the smaller design was interesting.

B. At Lightwave in December we had an internal kick off meeting for the detailed mechanical and electrical design tasks. One major issue arose at the design review: if we should proceed to package the 20 cm long amplifier or further investigate the folded design. Because we saw a great deal of excitement for the amplifier and this NASA contract was laying the groundwork for building more amplifiers in the near future we decided to spend the time to further test the folded design.

C. This folded amplifier testing extended into January. We found that although the folded version showed promise, it gave slightly lower efficiency than the earlier design. We committed to the earlier twin-parabolic design, and proceeded into detailed design of the deliverable prototype. However, the folded design is highly compact and we continued to develop it under our own funds for lower power applications such as fiber communications. This folded technology will provide part of the base for further (Phase III) commercialization.

D. We finished the layout design of the mechanical aspects of the amplifier. Detailing of the approximately 20 mechanical parts to the amplifier was followed by detailing of the jiggig for amplifier assembly. We finished the layout design of the mechanical aspects of the miniature oven to hold the LBO frequency doubling crystal, and design detailing followed. The overall optical head layout was underway.

E. The design of the electrical control boards to power the laser diodes, to cool the laser diodes, and to cool the laser crystal was done. Design was underway on the electronics to regulate the LBO oven and provide user interfaces and system interlocks.

F. The oscillator and oscillator drive electronics as well as the 10 to 15 watt fiber-coupled laser diode pump module were complete and operating well.

G. At this point we had made several pivotal decisions. We decided to use a single fiber pump from a multi-diode pump module, as opposed to more than one fiber because it makes the design much simpler, hence more reliable. This may limit our power, at least until improved diodes are available. We also decided to make an air-cooled system that could use either Nd:YAG or Nd:YVO₄ for either the oscillator or the amplifier.

Q8

A.. The deliverable laser source has two parts: the electronic controls and the optical system assembly. They are connected by electrical cable and optical fiber. The electronic controls contain two circuit boards and the laser diode module. The optical system assembly contains the oscillator, isolator, amplifier, doubling oven, and associated mode-matching optics. The mechanical layout was completed for the overall optical system assembly for holding and cooling the optical parts it contains. All optical components for the system assembly were ordered and arrived within the first 2 weeks of April. The mechanical detailing and fabrication for the optical system assembly's mechanical structure was also complete by that time. In March we finished the layout and most of the

mechanical detailing of the amplifier that goes in the optical system assembly. Parts were all ordered and fabricated. They were all ready by April 15. The oven for holding the LBO nonlinear doubling material was also done with layout and detailing, and fabricated. Testing of the oven will occur in the first 2 weeks of April. The oscillator was working and retested on the bench. Its performance was good.

B. The optical system assembly is optionally passively air cooled or cooled by fan air. This reduces the complexity as compared with water cooling. We use large heat-sink fins to remove heat, most of which is generated in cooling the laser crystal in the amplifier. The crystal is temperature regulated to keep its surface at about 0°C so as to keep its gain high and its gain-center matched to the oscillator. The prototype was built as a stand-alone laboratory system. The air cooling fin structure is simpler than water cooling which requires a radiator and fan. If the oscillator/amplifier system needs to be embedded in a larger system the heat sink fins can be removed from the prototype and the user can attach any available cooling source to our central aluminum cooling member. If external cooling structures or fluids were available to draw down the temperature of the amplifier's laser crystal then the system size and weight would be less. A cold ($\leq 20^{\circ}\text{C}$) external heat sink would improve the electrical efficiency by removing the need for thermoelectric coolers, and would also reduce the system size and weight dramatically.

C. The design of the electrical control boards to power the laser diodes, to cool the laser diodes, and to cool the laser crystal was done. Design was done on the electronics to regulate the LBO oven and provide user interfaces and system interlocks. The circuit boards have their electronic components soldered in place. The board that powers the diodes was debugged, and the oven control board was debugged. The mechanical structure layout for the electronic controls and laser diode module was done, and detailed. It fits within a 19" rack-mountable container that is about 5.5" high. This structure holds the laser diode module and the two main boards, one containing an AC to DC 28 volt power converter. Two fans cool this electrical structure. A smaller (~80 cfm) fan cools the electrical boards, and a larger (~120 cfm) square fan drives air past cooling fins for the fiber-coupled laser diode module. The fiber delivers light from the electronic control box to the system assembly.

D. Some Key Problems and Solutions on Deliverable Unit:

Wiring within the amplifier package was difficult because of the tight packaging. We used heater pads and solder to hold down the two parabolic mirrors, and the mirror that returns and focuses the diode light into the amplifier crystal. Each of 3 mirrors had two heater pads attached, and they mounted on top of two other pads so there were 12 pads with wires. In addition there were wires to the thermistor and to the TECs that temperature control the amplifier crystal. All these need to be routed to avoid the optical path and not block the mirror locations.

Spacers were used to help support the structure holding the amplifier crystal so the TECs would not bear full load. The spacers were too thin so the TECs do bear the load, but the two TECs are at 90° to each other, and they can bear most of the loading forces felt in compression, where they are rigid.

E. Transition to Phase III: We continued to work on plans for Phase III commercialization. The short-pulse Nd:YVO₄ oscillator technology that was developed as part of this program was already in Phase III, and commercially available. We explored the market for the amplifier technology. We initiated a project internally to test applications of the amplifier at fiber communications wavelengths where we are familiar with the markets. As part of the Phase III effort we publicized the results of this present NASA-supported work. Our CLEO submission for a talk in May 1993 on the amplifier was accepted and given. We are finalizing preparation of a manuscript for publication on the amplifier results. Our manuscripts on the short-pulse oscillator work and the amplifier work were accepted for publication.

Final Financial Summary. Our spending exceeded the budgeted rate. Detailed financial data is on the following page. The added costs were absorbed by Lightwave Electronics Corporation out of profits. The reasons for the added costs were (1) to make a sufficiently presentable prototype that the prototype could be commercially introduced and (2) to study reduced size versions of the laser amplifier for possible future use by NASA or in commercial applications. We feel these added efforts benefited both NASA and Lightwave Electronics Corporation.

Primarily Will Grossman (Principal investigator), Henry Plaessmann (optical engineer), Dave Vecht (senior mechanical engineer, designer of the amplifier), Kevin Yamada (mechanical engineer, designer of the frequency doubler to generate green light) and Joe Alonis (electrical engineer), Abbey Duran (mechanical engineer, designer of the diode housing and electrical control box), Carlos Rodriguez (mechanical drafter) and Sean Re' (optical physicist) worked on this program.

Date of end of summary period:	June 20, 1993
Contract Start:	May 22, 1991
Scheduled Completion:	June 28, 1993
Approximate % completion by time to date:	100%

	Direct Material	Direct Labor	Burdened total (without fee)
Budgeted total costs for full duration of contract	\$141,951	\$138,192	\$477,988
Actual accumulated costs:	\$127,514	\$ 114,721	\$ 408,839
Accumulated costs % of budget	89.8%	83.0%	85.5%

Direct labor hours.

cumulative to date:	4332
budgeted in contract	5,880

3. Part C. Delivered system and test data overview

The delivered system has optical components and controllers. They are shown in Fig. 10 below. The system consists of the parts listed below. All these parts were custom made for this project except the isolator.

- Laser diode pump module (within the larger controller box in Fig. 10)
- Optical fiber from module to multi-pass amplifier
- Oscillator (Model 111V within the black optical assembly in Fig. 10)
- Optical isolator (gold cylinder in black optical assembly in Fig. 10)
- Amplifier (Model 160 in black optical assembly in Fig. 10)
- Second harmonic generation doubler in oven (in black optical assembly in Fig. 10)
- Structure to carry beam from oscillator to amplifier to doubler
(in black optical assembly in Fig. 10)
- Power supply driving and containing diode module
(The larger controller box in Fig. 10; it also controls doubler and amp)
- Power supply and controller for oscillator
(The smaller controller box on top of the larger box in Fig. 10)
- Power supply (24 V 0.5 A) for fans under structure carrying amp (not shown)

ORIGINAL PAGE
COLOR PHOTOGRAPH

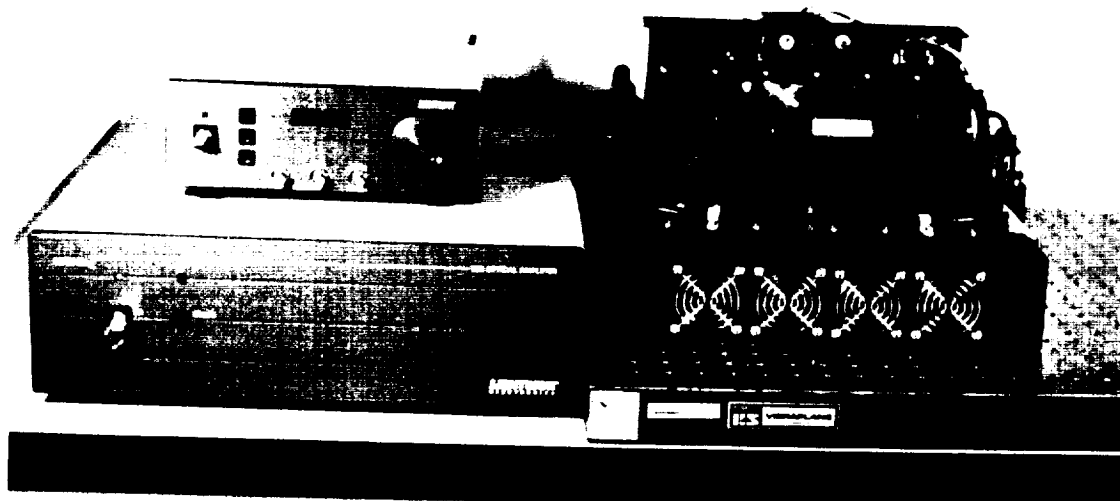


Figure 10. The delivered system with the electrical controllers on left and the laser oscillator, amplifier, and doubler on the right.

Spectrum: The output of the system can be either pulsed or cw, and can be with or without the doubler present. With the doubler the output is at 0.532 μm . Without the doubler the output is at 1.064 μm . Based on measurements of the oscillator, the spectral width at 1.064 μm is typically about 60 GHz, composed of about 6 modes each spaced by about 12 GHz. The second harmonic (green) spectral width is about twice the 60 GHz width at 1.064 μm .

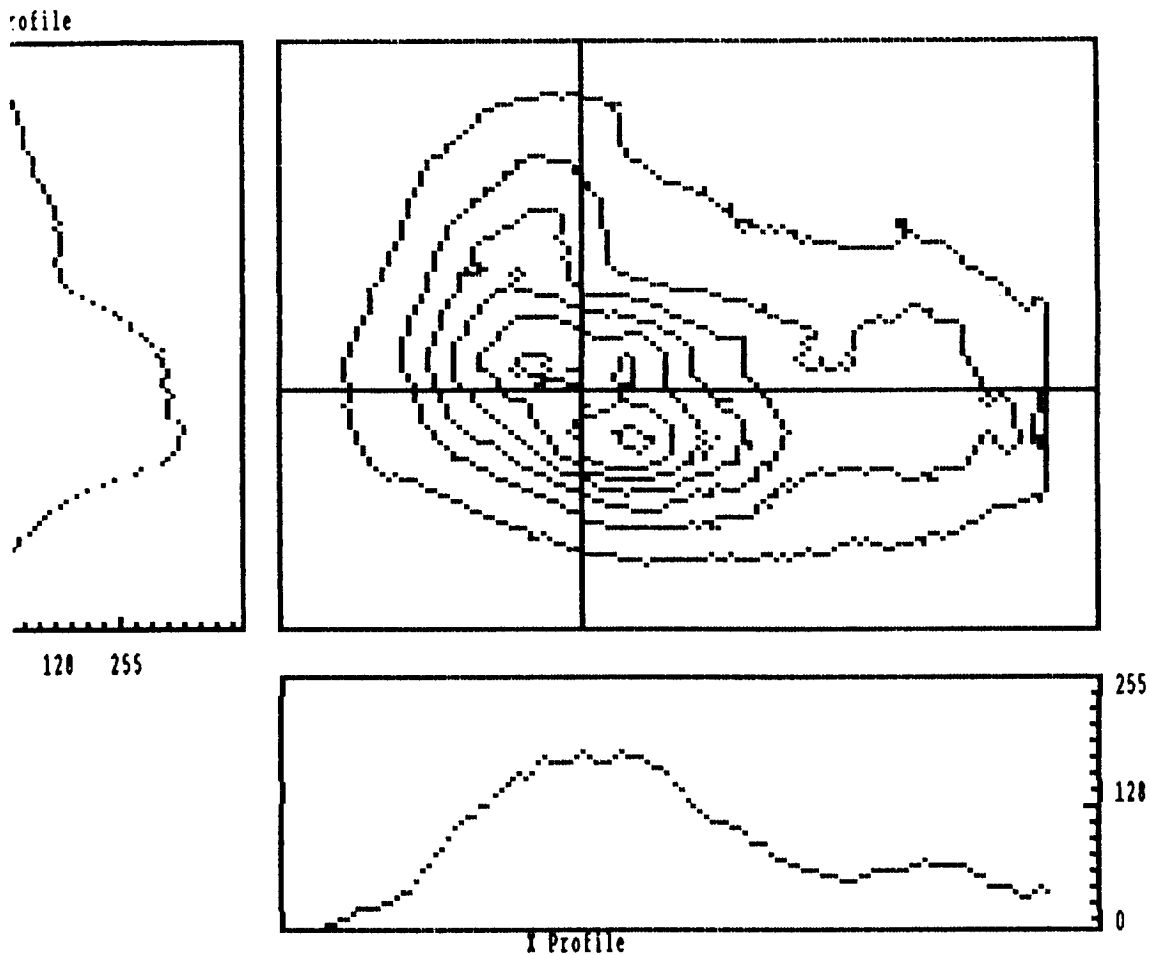
Beam Quality: The beam quality is good at high repetition rates, but degrades at lower rates as the oscillator has trouble switching quickly enough for the short build-up times at lower repetition rates. This is shown in Figures 11-13.

Power and Pulse widths: The power and pulse widths are given in Table 5 below, and in Figures 14-16.

Table 5. Output power and pulse width at different repetition rates on delivered unit.

Repetition Rate (kHz)	Average Power in green (watts)	Pulse width (ns) (measured on scope direct)
1	.056	1.25
2.5	.145	
5	.321	
7.5	.530	
10	.718	1.25
12.5	.833	
15	.923	
17.5	.974	
20	1.00	1.5
25	1.00	
30	.962	
35	.897	
40	.833	1.9
45	.782	
50	.731	
60	.628	2.0
70	.538	
80	.474	2.8
90	.397	
100	.346	3.5

Beam Profile by BeamGrabber 6100 from Photon, Inc.



ent Settings:

Display Delta = Off
Autocenter = On
X Reference = 2383 u
Gain = 0

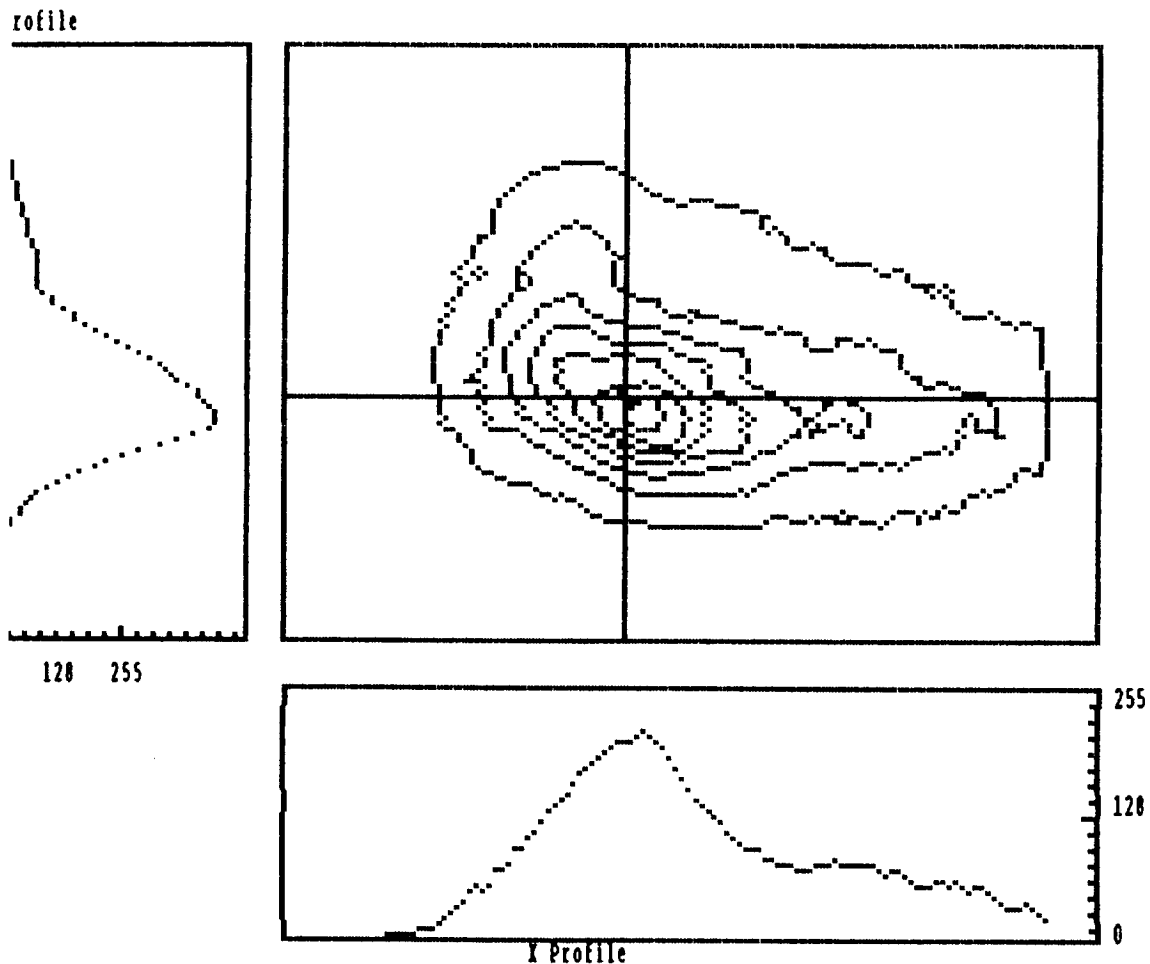
Clip Level = 13.5%
Sample Averaging = 1
Y Reference = 2574 u
B Reference = 852592

ults:

Value

3170u
178
83 %
-1 u
-22 u

Figure 11. Amplified green beam profiles at 1 kHz pulse repetition rate; beam profile reflects oscillator profile, and is astigmatic, and differs substantially from Gaussian.



rent Settings:

Display Delta = Off
Autocenter = On
X Reference = 2383 u
Gain = 0

Clip Level = 13.54
Sample Averaging = 1
Y Reference = 2574 u
B Reference = 852592

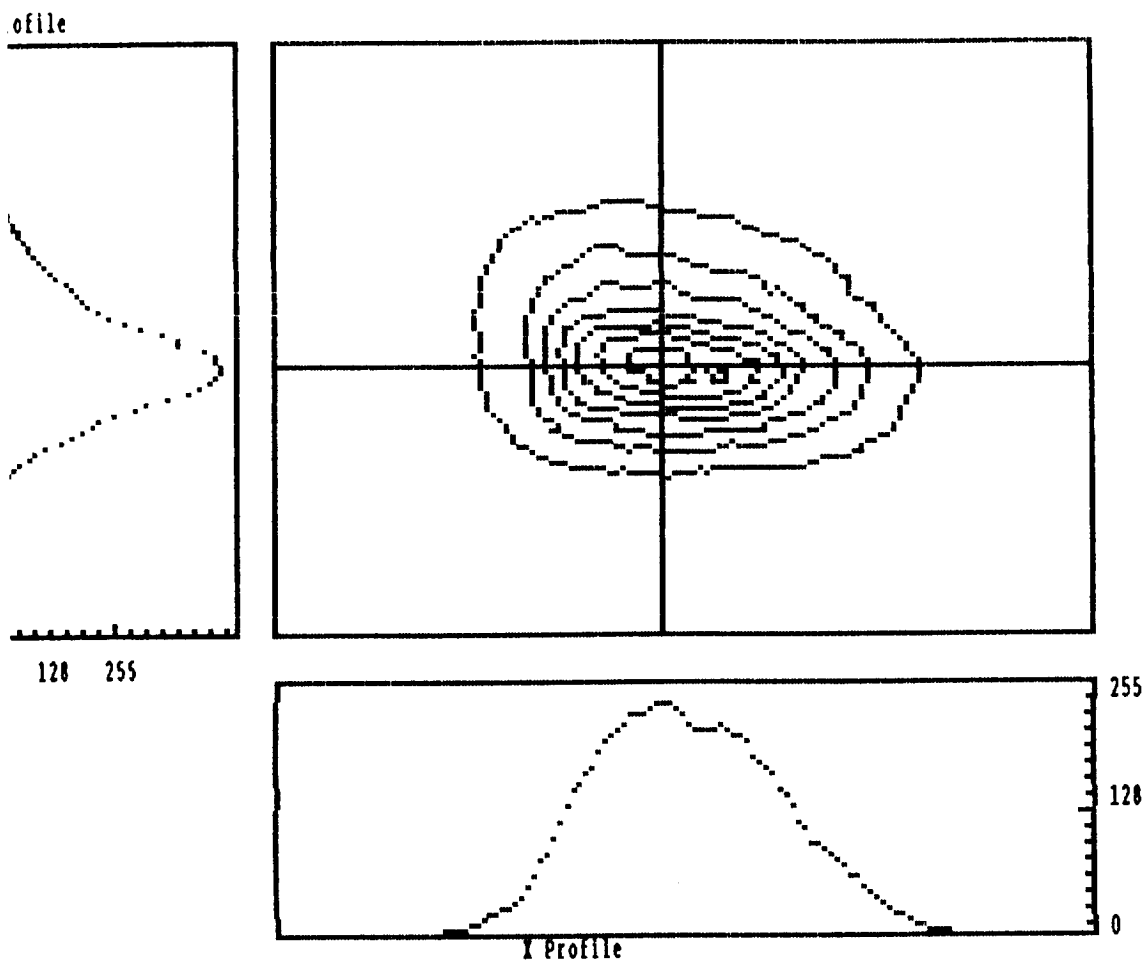
ults:

Value

2137u
200
54 %
306 u
14 u

Figure 12. Amplified green beam profiles at 10 kHz pulse repetition rate; beam profile reflects oscillator profile, and is astigmatic, and differs from Gaussian.

Beam Profile by BeamGrabber 6100 from Photon, Inc.



ent Settings:

Display Delta = Off
Autocenter = On
X Reference = 2383 u
Gain = 0

Clip Level = 13.5%

Sample Averaging = 1

Y Reference = 2574 u

B Reference = 852592

ults:

Value

+++++

+++++

231

54 %

665 u

206 u

Figure 13. Amplified green beam profiles at about 50 kHz pulse repetition rate; beam profile reflects oscillator profile, and is astigmatic, but not far from Gaussian.

Timing Jitter: the pulse timing jitter at 20 kHz is

- ±5 ns with respect to a trigger in
- ±1 ns with respect to a trigger out or to either a trigger in that is
synchronous with the RF drive in the Model 111 pulsed laser head.

Pulse to Pulse Stability: Table 6 along with Figure 17 shows the pulse amplitude stability.

Table 6. Output pulse stability at different repetition rates on delivered unit.

Repetition Rate (kHz)	Pulse amplitude stability % from scope (peak-to-peak) / mean
1	9
5	9
10	17
20	26
40	50
60	67
80	75
100	75

Structure to carry beam from oscillator to amplifier to doubler:

The structure has:

- 2 lenses between the oscillator and the isolator
(lens 1 closest to the oscillator and lens 2)
- a half-waveplate between the isolator and the amplifier
- 2 lenses between the isolator and the amplifier
(lens 3 closer to the isolator and lens 4)
- a half-waveplate between the amplifier and the doubler
- 2 lenses between the amplifier and the doubler
(lens 3 closer to the amplifier and lens 4)

The lenses are plano-convex or concave as defined by their focal lengths and antireflection coated for use at 1.064 μm .

- lens 1: focal length +75 mm plano side faces oscillator
- lens 2: focal length -75 mm plano side faces oscillator
- lens 3: focal length -500 mm plano side faces amplifier
- lens 4: focal length +125 mm plano side faces amplifier
- lens 5: focal length +100 mm plano side faces doubler

Principal plane to principal plane and other nominal spacings (the doubler location is the center plane of the doubler; the amplifier location is the center plane of the amplifier):

- lens 1 to lens 2: 101 mm
- lens 2 to lens 3: 312 mm
- lens 3 to lens 4: 80 mm
- lens 4 to amplifier: 135 mm
- lens 5 to doubler: 193 mm

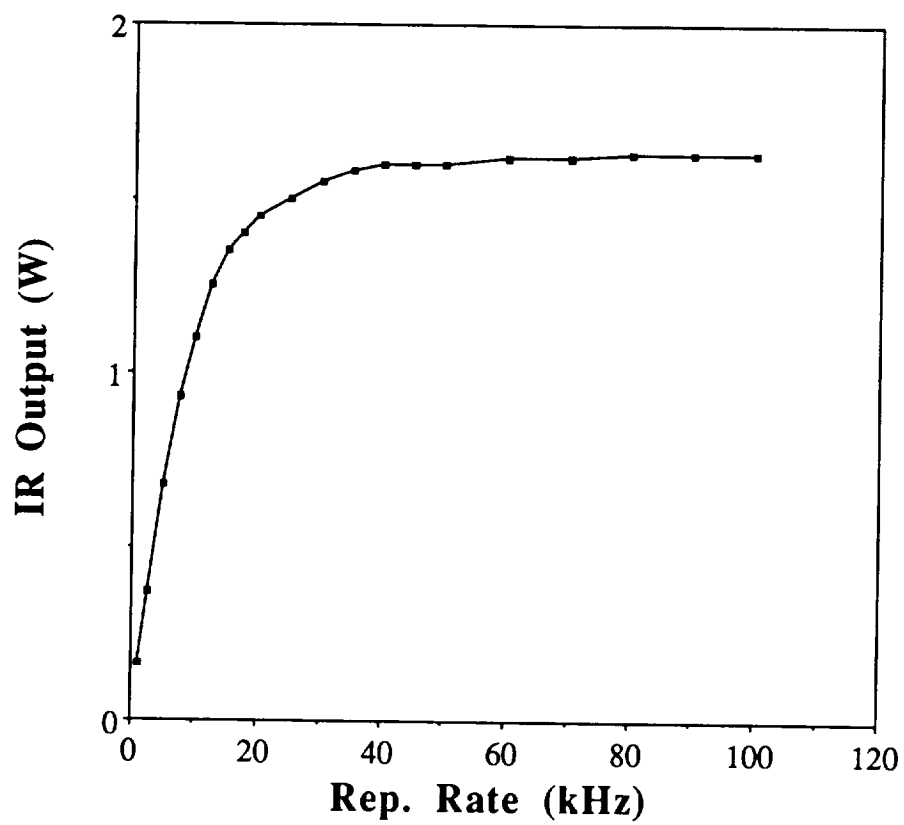


Figure 14. Average 1 μm infrared power as a function of repetition rate for the delivered laser.

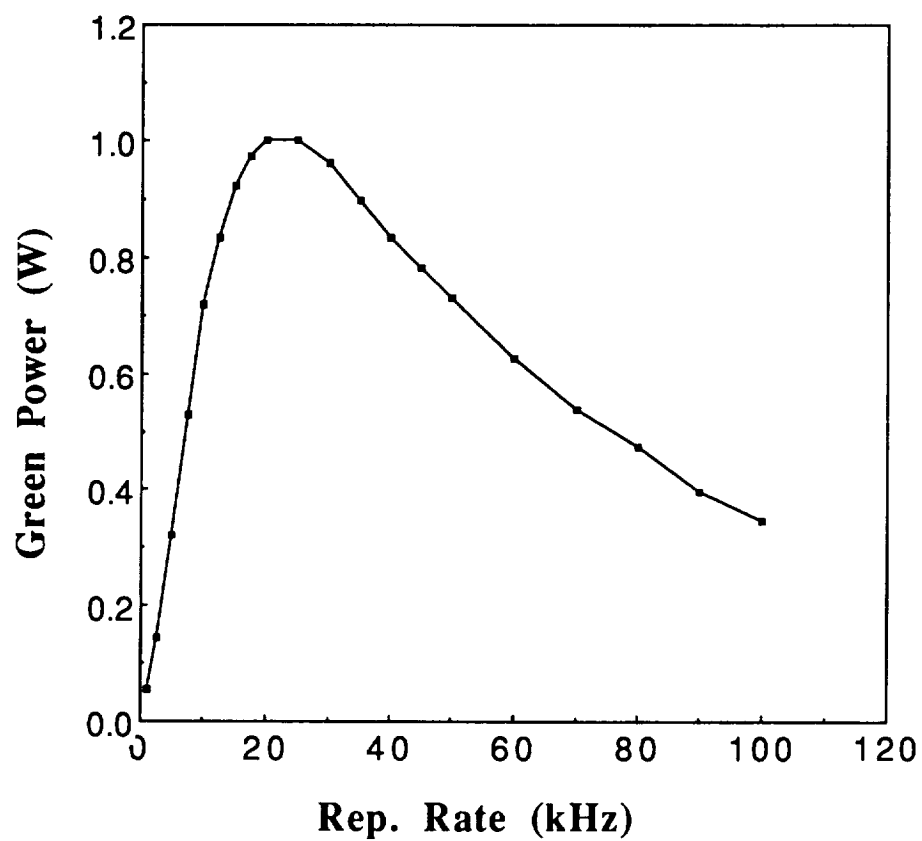


Figure 15. Average green 0.5 μm power as a function of repetition rate for the delivered laser.

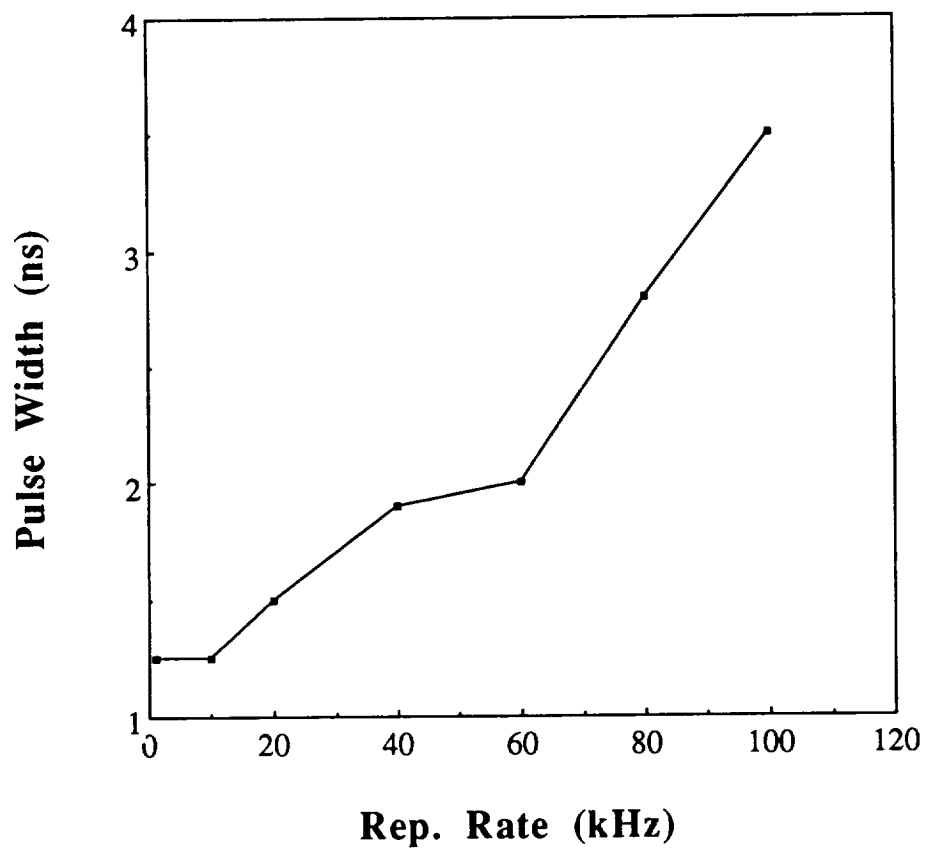


Figure 16. Average green 0.5 μm pulse width (FWHM) as a function of repetition rate for the delivered laser.

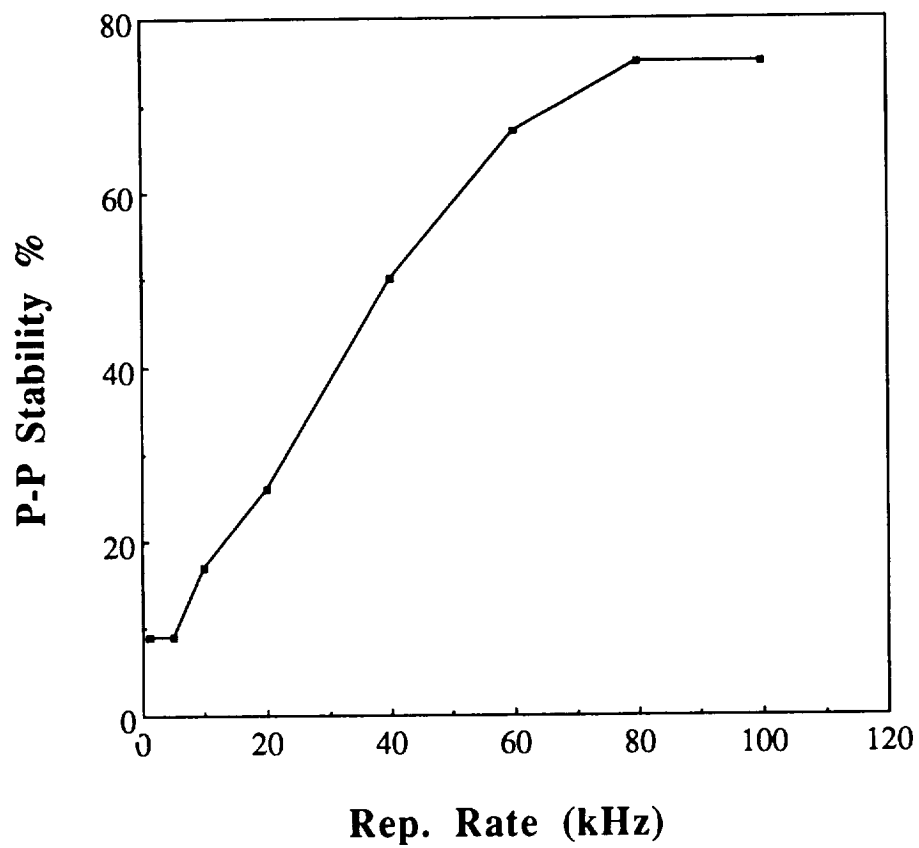


Figure 14. Peak-to-peak pulse amplitude stability at 0.5 μm as a function of repetition rate for the delivered laser. Stability is expressed as a percent of the mean amplitude.

High Gain Diode CW-Pumped Solid-state Optical Amplifier

Henry Plaessmann, Joseph J. Alonis, Sean A. Re, David L. Vecht,
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November 16, 1992

Abstract

A diode cw-pumped solid-state optical amplifier produces 40 dB small signal gain and > 4 W saturated output power at $1.064 \mu\text{m}$. When $2 \mu\text{J}/700 \text{ ps}$ pulses are input from a diode pumped acousto-optically Q-switched solid-state laser operating at 1 kHz, $500 \mu\text{J}/1 \text{ ns}$ pulses are output from the amplifier.

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High gain, cw amplification¹ is a technique which boosts low output powers from diode pumped solid-state laser systems while adequately preserving desirable spectral, amplitude, phase, or pulse width characteristics available from only these devices. This paper presents a high gain, multiple pass, diode cw-pumped, solid-state optical amplifier.

The amplifier uses 2 symmetrically confocal parabolic mirrors with the gain medium centered between them. Light is input through a center hole in one of the mirrors. Up to 14 passes are achieved by inserting a flat glass plate adjacent to the gain medium at Brewster's angle (see Fig. 1). The Brewster's angle plate displaces the beam by an amount proportional to the plate thickness, so that after each successive "bow-tie" round trip, the beam moves farther from the optical axis until it finally misses the parabolic mirror opposite the input hole, and the beam is output from the amplifier.^{2,3}

Pumping Nd:YLF at 798 nm with 1.6 W incident in a 200 μm diameter mode yields approximately 40 dB small signal gain and 620 mW saturated output--an optical-to-optical conversion efficiency of about 38%. Input is 35 mW cw power from a Nd:YLF oscillator.⁴

With Nd:YAG as the gain medium, and pumping with 13 W of 805 nm diode laser light incident on the YAG in a 400 μm diameter mode, 3.2 W saturated output is achieved. Input in this case is 640 mW cw from a single-frequency Nd:YAG ring laser⁵, and the

High Gain Diode CW-Pumped Solid-state Optical Amplifier

Henry Plaessmann, Joseph J. Alonis, Sean A. Re, David L. Vecht, William Grossman

conversion efficiency is 20%. Changing the input to a 20 mW average power acousto-optically Q-switched Nd:YVO₄ laser⁶ produces 2.4 W average power, 1.5 ns, 20 kHz pulses output. Frequency doubling this output in type I LBO yields 1.5 W average second harmonic power corresponding to a 63% conversion efficiency from the infrared to the green. At 1 kHz the system delivers 1.0 ns, 500 μ J pulses at 1.064 μ m.

Nd:YVO₄ can also be used as the amplifying medium. With the same pumping and input parameters as in the YAG amplifier experiments, the Nd:YVO₄ amplifier generates 4.3 W cw single-frequency power (33% conversion--see Fig. 2), or 3.0 W pulsed average power with 1.5 ns pulse durations at 20 kHz.

The amplifier described herein is applicable to modulated, cw, short or long pulsed input, and it is wavelength versatile. Further details of the amplifier design and results such as thermal aspects of the gain media, amplified spontaneous emission, and parasitic oscillation suppression will be discussed. Higher power scaling experiments of up to 20 W pump power will be discussed as well.

High Gain Diode CW-Pumped Solid-state Optical Amplifier

Henry Plaessmann, Joseph J. Alonis, Sean A. Re, David L. Vecht, William Grossman

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High Gain Diode CW-Pumped Solid-state Optical Amplifier

Henry Plaessmann, Joseph J. Alonis, Sean A. Re, David L. Vecht, William Grossman

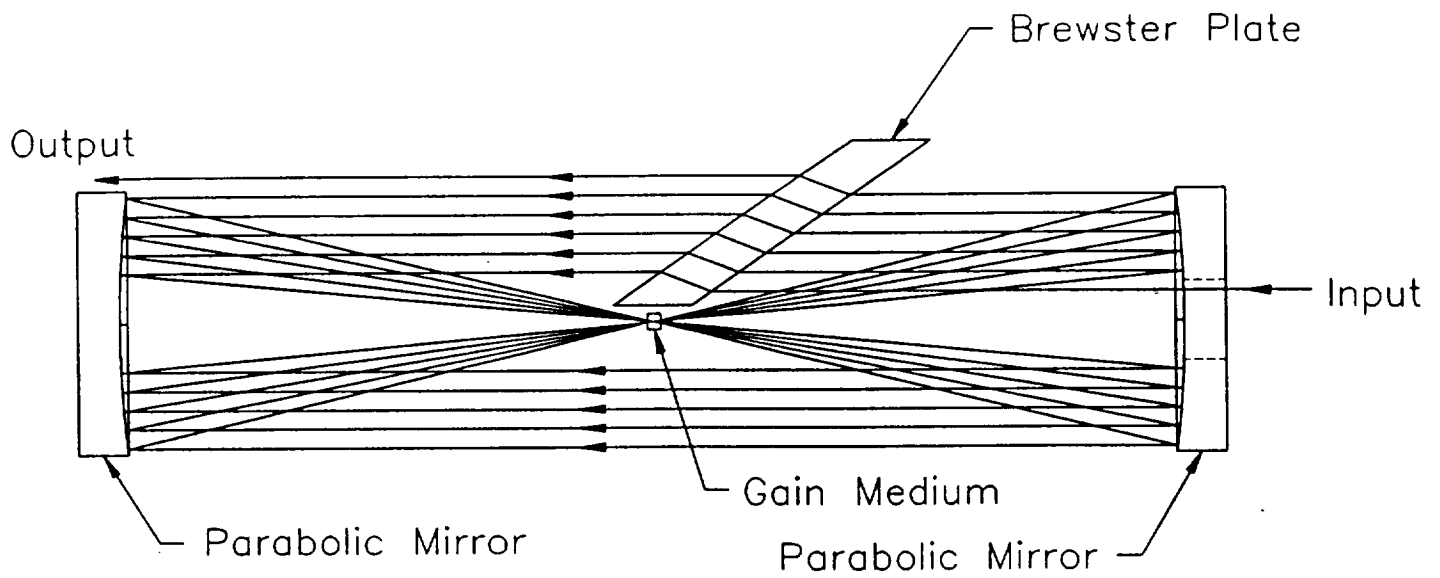


Figure 1

High Gain Diode CW-Pumped Solid-state Optical Amplifier

Henry Plaessmann, Joseph J. Alonis, Sean A. Re, David L. Vecht, William Grossman

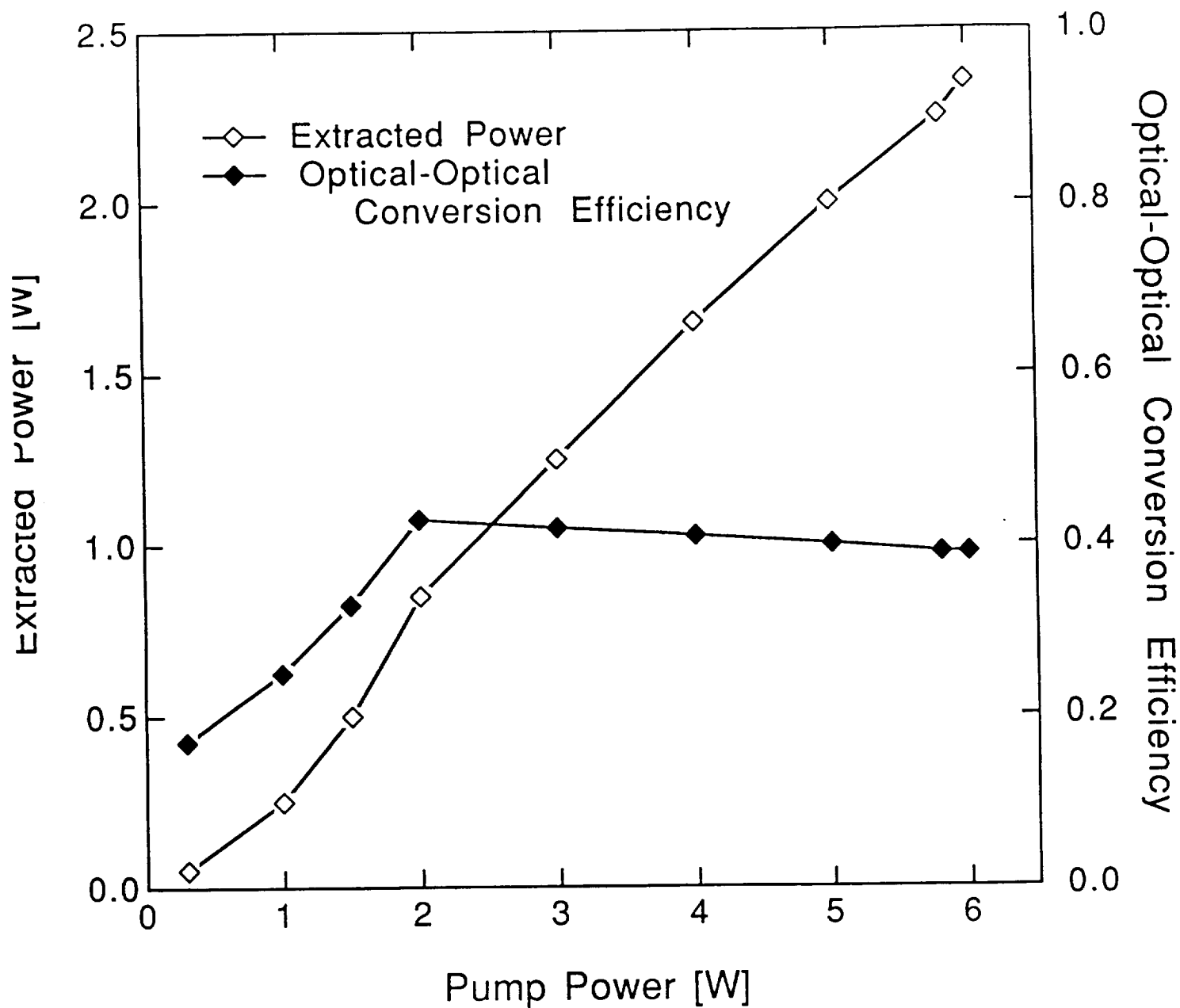
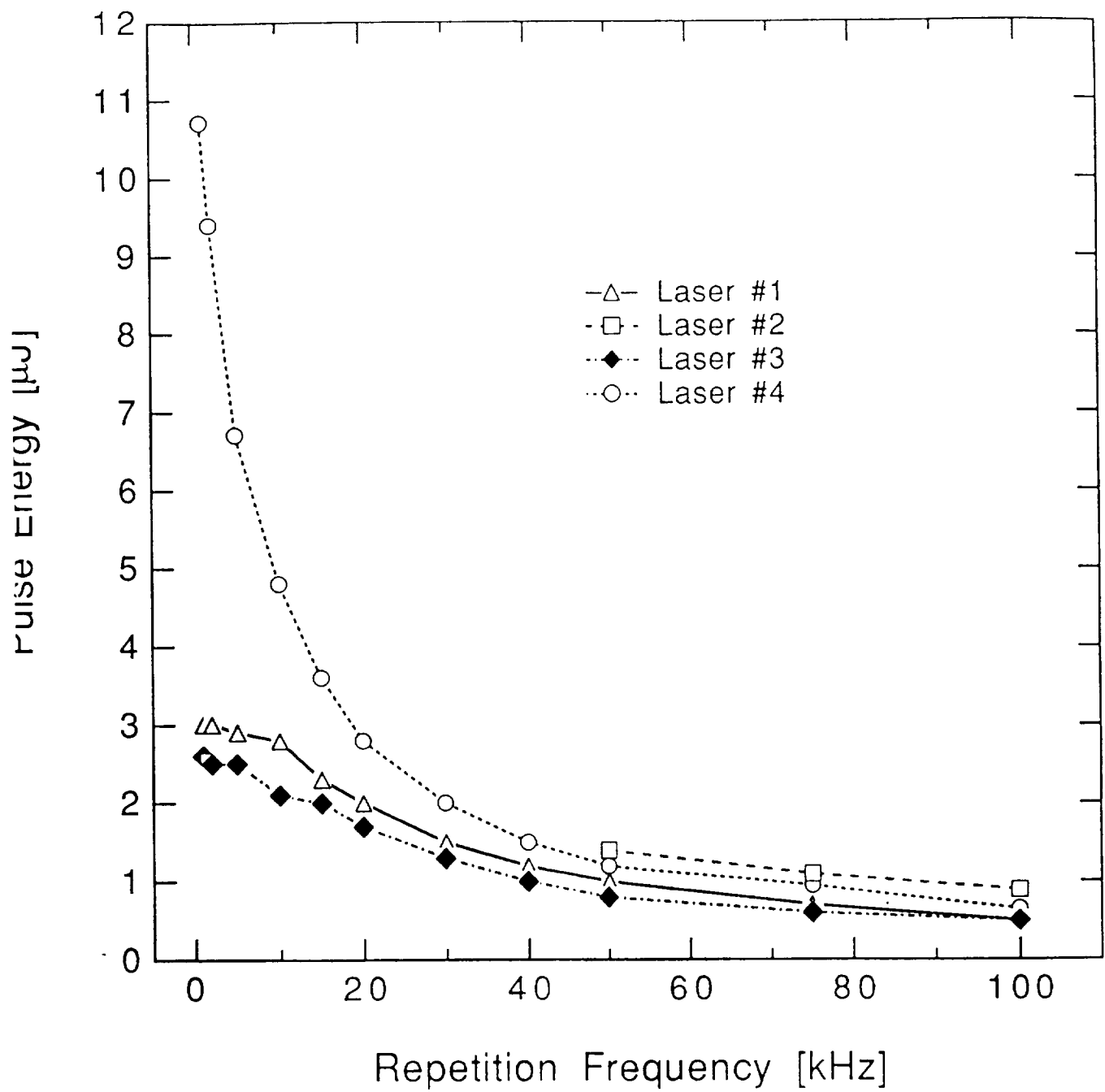
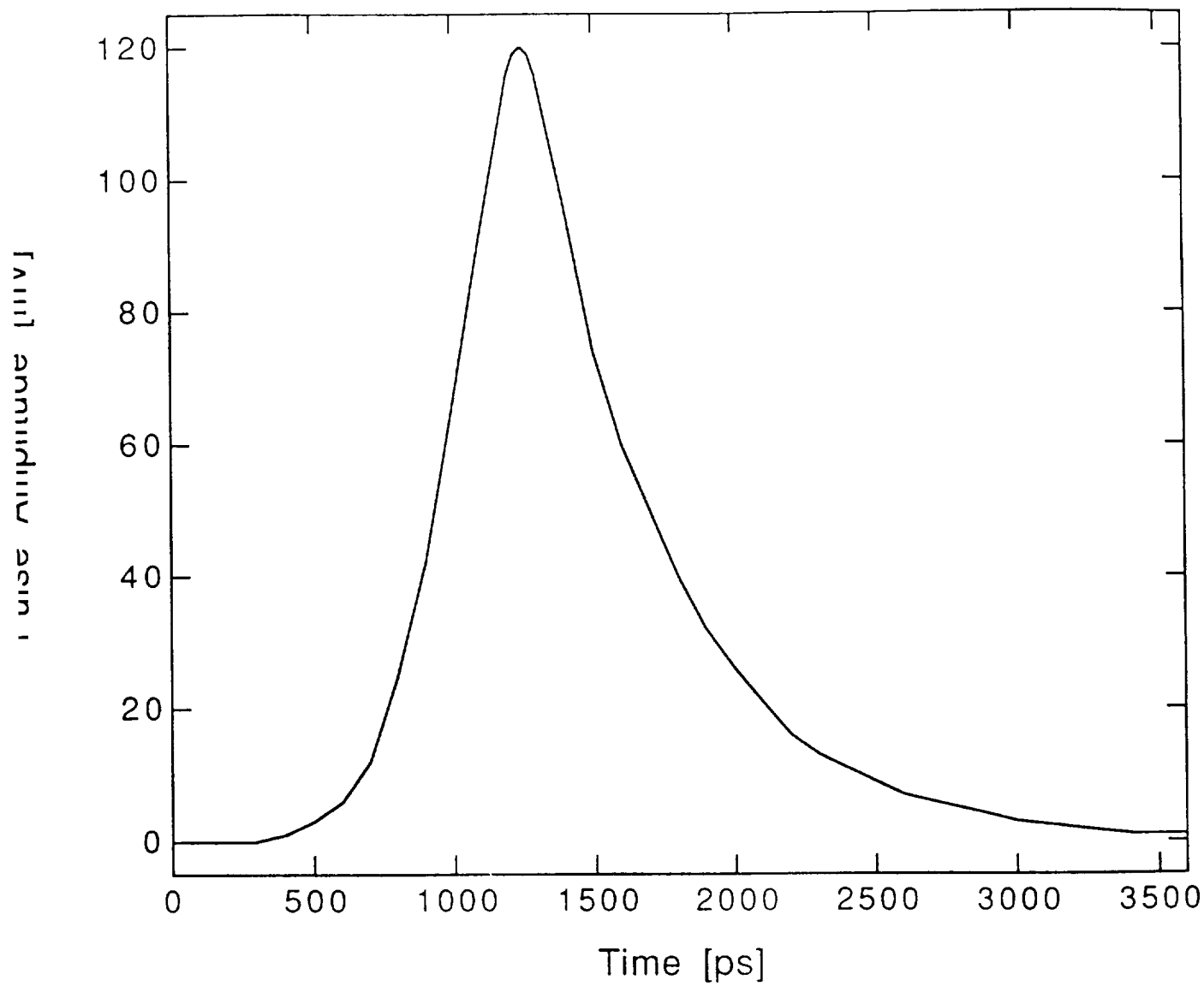


Figure 2





Figure/Table Captions:

Table 1. Resonator parameters.

Fig. 1. Nd:YVO₄ laser configuration. M1 is flat, HR at 1.064 μm and HT at 0.808 μm . M2 has 15 mm radius and 25% or 65% transmission at 1.064 μm . Q-switch and output coupler materials are TeO₂ and SiO₂ respectively. Diode polarization is parallel to Nd:YVO₄ crystal axis. Resonator components are separated by Brewster's angle air gaps, and physical cavity length is 7 mm.

Fig. 2. Pulse duration as a function of repetition frequency. Indicated percents refer to output coupler transmission.

Fig. 3. Pulse energy as a function of repetition frequency. Indicated percents refer to output coupler transmission.

Fig. 4. Pulse trace for the 1.064 μm Nd:YVO₄ laser with 65% output coupling operating at a repetition frequency of 1 kHz--pulse width is 600 ps FWHM.

Multi-pass Diode Pumped Solid-State Optical Amplifier

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March 18, 1993

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Abstract

A new diode pumped solid-state multi-pass amplifier produced 38 dB small-signal gain at 1.047 μm in Nd:YLF with 1.6 W pump power, and 37% extraction efficiency near saturation. The amplifier had a 1:1 confocally reimaging multi-pass design that generated both high gain and high efficiency. The same amplifier design with 13 W of pump power was tested using Nd:YAG at 1.064 μm giving 38 dB small-signal gain and 3.2 W of output power, and with Nd:YVO₄, also at 1.064 μm , giving >50 dB small-signal gain and 4.3 W of output power.

High gain and efficient amplification of light is desirable in many applications. Achieving high gain with laser diode pumped systems is challenging, although diode end-pumping produces high efficiency [1, 2]. Optical fiber amplifiers offer an elegant solution for efficient and high gain amplification if fibers are available with gain at the desired wavelengths and if the peak optical powers involved do not damage the fibers. Amplification in bulk laser materials, as opposed to fibers, permits high peak powers in TEM₀₀ modes and versatility in the choice of gain materials. For example, diode pumped Nd:glass [3] and Nd:YLF [4] regenerative amplifiers produced 51 dB and 73 dB of gain respectively with 2 W of pump power. An alternating precessing slab Nd:YAG amplifier generated 16 dB double pass gain with 36 mJ of diode pump energy from four 2-bar pulsed diode stacks [5], and a tightly folded amplifier pumped by a 10 W CW diode bar produced a double pass gain of 25 dB [6]. Recently developed efficient multi-pass Ti:sapphire and dye amplifiers used unique confocal geometrical designs to reimage each successive pass through a single gain element. Lamp-pumped solid-state lasers, which are near diffraction-limited, pumped these multi-pass amplifier systems. Two such amplifiers had confocally aligned spherical mirrors of slightly different radii with a multi-pass reimagining beam path, and produced gain as high as 63 dB [7,8]. In these cases the different mirror radii caused the beam diameter within the laser material to grow in a geometrical progression from pass to pass. A 1:1 multi-pass amplifier embodiment was reported that used confocally aligned lenses of equal focal lengths and several separate 180 degree folding mirrors to produce about 90 dB of small-signal gain, again using a lamp-pumped Nd:YAG-based pump system [9].

This Letter describes a multiple pass amplifier with 1:1 confocal mirror reimagining. Distinguishing characteristics of this work are that the amplifier is diode-pumped and we report a new simple polarizing 1:1 imaging design. The 1:1 reimagining is important because it allows the gain profile to match the input beam diameter on each

pass, contributing to good beam quality and high efficiency. The design accepts a large range of pump beam sizes and pump powers to produce high gain and high extraction efficiency. To our knowledge this geometry produces the highest gain per watt of pump power of any bulk solid-state optical amplifier. This is the first report of a diode-pumped multi-pass amplifier design with 1:1 reimaging, and it is both the highest small-signal gain and extraction efficiency reported for any diode pumped CW amplifier. Pulsed and continuous wave experiments near 1 μm in Nd:YLF, Nd:YAG, and Nd:YVO₄ are discussed; thermal focusing compensation and parasitic oscillation suppression are also addressed.

Fig. 1 shows the amplifier design and pumping arrangement. Two parabolic mirrors, each having 51 mm diameter and 102 mm focal length, are aligned confocally, and share a common central axis. The parabolic surfaces are 99.9% reflective at 1 μm and 95% transmissive at 0.8 μm , and the flat back mirror surfaces are anti-reflection coated at 0.8 μm . Mirror 2 has a center hole of 9.5 mm diameter for beam input. The gain medium is located on axis at the common focus of the parabolas. Amplifier gain materials are either Nd:YLF, Nd:YAG or Nd:YVO₄, and the chosen crystal is held stress-free and cooled on two opposing sides at about 5 °C by thermoelectric coolers. With Nd:YLF and Nd:YVO₄ the crystal c-axis is oriented in the plane of Fig. 1 approximately orthogonal to the beam paths.

Optics external to the amplifier, and not shown in Fig. 1, direct the input beam parallel to the central amplifier axis so that the beam focuses to an initial waist as it passes beside the gain medium. An uncoated fused silica Brewster plate with flat and parallel surfaces is adjacent to the gain medium shown in Fig. 1. This Brewster plate linearly translates, or displaces, the incident beam path in a direction (x) orthogonal to the central axis so that the optical path never replicates. The Brewster plate also

discriminates in favor of a linear polarization for the beam under amplification. In this design the plate thickness gives a spacing of 2.5 mm between each successive pass. The input beam is inserted into the amplifier through a hole in parabolic mirror 2 with the input beam path is offset by approximately +3.25 mm from the central axis. After passing through the Brewster plate the beam path is then offset by about +5.75 mm. Mirror 1 then reflects the beam path through the gain medium which amplifies the beam. The beam path is next incident on mirror 2, offset by -5.75 mm, and after reflection the beam path is parallel to the central axis and passes back to mirror 1 where it reflects again toward the gain medium so it is next incident on mirror 2, offset by +5.75 mm. Mirror 2 reflects the beam path parallel to the central axis and toward the Brewster plate where the cycle of displacement and amplification is repeated. The beam path weaves through the gain medium up to 14 times in this arrangement.

When aligned as described all the legs of the optical path lie in a single plane. In the Fig. 1 the beam passes through the gain in approximately the same direction (left to right) on each pass, and the beam is reimaged from pass to pass of the gain medium after reflecting from the two parabolas. The diameter of the waist internal to the gain medium is inversely proportional to diameter of the input beam waist located beside the gain medium, and in the plane of the gain medium. Consequently, the size of the input beam waist beside the gain medium dictates the waist diameter for all successive passes of the gain medium, even in the presence of thermal lensing at the gain medium. With no amplification, the 14-pass system attenuates the input beam by about 20%.

The amplifier was pumped through parabolic mirror 1 opposite the input end. The 1:1 pump imaging optics shown in Fig. 1 consisted of twin adjacent antireflection coated achromatic lenses with 120 mm focal lengths. When Nd:YLF was the amplifier gain medium the pump was a Spectra Diode Labs model 2470-C laser diode with a 200

μm emitting aperture and a wavelength of 798 nm. A small cylindrical lens captured the pump light in the rapidly diverging dimension. The pump light exiting this lens was reimaged by the twin achromats shown in Fig. 1. For the higher power tests with Nd:YAG as the amplifying gain medium we used a 400 μm diameter numerical aperture 0.25 source that delivered up to 13 W at the amplifier gain medium [10]. The pump wavelength available for pumping Nd:YAG and Nd:YVO₄ was 805 nm. The higher pump power was not used with Nd:YLF which fractured with just 6 W of pump.

CW and Q-switched oscillators were used in these tests, and their characteristics are listed in Table 1. The 1.064 μm CW oscillator is a single-longitudinal-mode nonplanar-ring laser oscillator [11, 12]. The 1.064 μm CW oscillator was amplified by Nd:YAG or Nd:YVO₄ amplifiers. The 1.047 μm CW oscillator is a multi-mode Nd:YLF oscillator [13]. The acousto-optically Q-switched Nd:YVO₄ oscillator has a TeO₂ acousto-optic switch and a total cavity length of 7.5 mm, and is otherwise similar to the design of ref. 13. The Q-switched Nd:YVO₄ oscillator was amplified by Nd:YAG or Nd:YVO₄ amplifiers.

Two mechanisms that can rob power from the amplifier are parasitic oscillations and amplified spontaneous emission (ASE). Parasitic oscillations are unwanted laser emission occurring outside the amplifier's beam path, and these oscillations have a threshold. In contrast, ASE is emission occurring along the amplifier beam path and has no threshold. With all the amplifiers tested, parasitic oscillations could occur out of the plane of the beam paths in Fig. 1, but a simple aperture, such as a paper card, placed to the left of parabolic mirror 2 and out of the plane of the Figure suppressed all parasitic oscillations. ASE is not easily suppressed if the available gain is large, but ASE decreases when a beam is input to the amplifier, power is extracted, and the gain is saturated. The output mirrors from either the linear Nd:YLF or Nd:YVO₄ oscillator

back-reflected the amplifier's ASE so that it double-passed the amplifier, doubling the already large small-signal gain, and bring the ASE to watt levels in some cases. To suppress unwanted ASE we inserted a Faraday isolator between these linear oscillators and the amplifier. This isolation was not needed with the Nd:YAG ring laser oscillator which emits output at non-normal incidence from its output coupling surface.

Table 2 is a list of experimental parameters and results. Plots of extracted power as a function of gain are shown in Fig. 2. The gain (in dB) is the relative power of the amplified output with respect to the throughput of the oscillator without amplification. The extracted power is the difference between the amplified output and the throughput of the oscillator without amplification. Theoretically the data falls on a straight line for each family of data points taken using one amplifier gain material and pump [14]. However, power dependent effects such as extraction dependent thermal changes cause small nonlinearities. For each family of data points in Fig. 2 the input power to the amplifier was varied by attenuation, while the pump power to the amplifier was kept constant. The extrapolated intercept with the vertical axis is the theoretical maximum power available with large input oscillator power, and the extrapolated intercept with the horizontal axis is the small-signal gain. Fig. 2 indicates a small-signal gain of 38 dB for the 1.047 YLF/YLF oscillator/amplifier system with an incident pump power of only 1.6 W in a 200 μm diameter mode. The highest measured extraction was 0.62 W in the CW regime which corresponds to 37% optical-to-optical conversion efficiency. The ASE was about 9 mW with no input. Thermal lensing was not evident in this experiment. Because of equipment availability, the Nd:YAG amplifier data in Fig. 2 used 10.2 W of pump and optics different than used in Table 2, but the pump had the same magnification, N. A., wavelength, and source size as in Table 2.

With 13 W of pump the Nd:YAG amplifier gave a small-signal gain of 38 dB, and 3.2 W single-frequency output with 20% efficiency. In this case a pair of -200 mm focal length lenses were inserted symmetrically around, and adjacent to, the Nd:YAG gain material for some compensation of the positive thermal lens in the Nd:YAG due to the pumping. The insertion loss of these lenses was a cause of reduced efficiency, and concave surfaces polished on the Nd:YAG can improve this performance. The Nd:YAG amplifier with 13 W of pump generated about 60 mW ASE.

Thermal lensing in Nd:YVO₄ was asymmetrical at high pump power, and as in the case with the Nd:YAG amplifier, a pair of -200 mm focal length lenses were inserted symmetrically around the Nd:YVO₄ amplifier gain medium to achieve some degree of compensation, although stronger lenses would be required for full correction. Under these conditions with the CW Nd:YAG oscillator 4.3 W of single frequency light was output. With the pulsed Nd:YVO₄ oscillator output was as high as 150 μ J with 1.5 ns duration at 20 kHz, and with 120 μ J (2.4 W) incident on LBO, 75 μ J (1.5 W) of second harmonic was generated with 63% efficiency. With hundreds of milliwatts input the extraction efficiency from the Nd:YVO₄ amplifier was high and parasitics were not evident, but with input power below a few milliwatts the ASE was as much as 0.5 W. The small-signal gain is extrapolated to be 50 dB to 57 dB from several CW and pulsed (respectively) saturated gain measurements assuming a linear scaling of gain with power. The Nd:YVO₄ crystal suffered thermally induced fracture during our tests with 13 W of pumping.

With pulsed input the amplifier output pulse widths were changed by at most 0.5 ns out of 1 to 5 ns pulses in our measurements. Changes at low repetition rates may be due to preferential amplification of the leading edge of the pulses or due to slight measurement errors. With CW input the noise spectrum of the output matched that of the

input as measured on a spectrum analyzer, indicating the amplifier displayed nothing analogous to relaxation oscillations characteristic of laser oscillators.

In conclusion, high gain and efficient diode-pumped Nd:YLF, Nd:YAG, and Nd:YVO₄ multi-pass amplifiers operating near 1 μm were developed and characterized. The design accepted at least a two-fold range of input TEM₀₀ beam diameters and either CW or pulsed input. Efficiency up to 38% and in another test gain \geq 50 dB was demonstrated at CW pumping levels of 1.6 W and 13.0 W respectively. Amplification using identical oscillator and amplifier gain materials or mixing Nd:YAG and Nd:YVO₄ oscillator and gain materials all gave high efficiency and large small-signal gains. Furthermore, high multi-pass gain is expected for other solid-state gain materials and at other laser wavelengths such as 1.3, 1.5, and 2 μm using 1:1 confocal designs. Many planar and out-of-plane design variations are possible to optimize the amplifier for particular pumps and number of passes.

We would like to thank Dr. Dave Shannon for helpful discussions and for leading the development work that produced the 13 W diode pump module. We gratefully acknowledge the support of the National Aeronautics and Space Administration contract NAS7-1145 and technical guidance from the Jet Propulsion Laboratory. This contract is part of the Small Business Innovative Research (SBIR) program.

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Figure Captions

Figure. 1 The amplifier design uses two parabolic mirrors of equal focal length aligned confocally for 1:1 reimaging with the gain medium located at the focal plane. Multiple passes are achieved by means of a Brewster angled plate which displaces the beam path after each pass through the gain medium. Beam input is through a center hole in parabolic mirror 2, and the laser crystal is pumped through parabolic mirror 1.

Figure. 2 Extracted power as a function of gain (in dB) for Nd:YLF and Nd:YAG amplifiers using 1.6 and 10.2 W of pump respectively, the experimental conditions listed in Tables 1 and 2, and CW oscillators. The pump power to the amplifier is kept constant for each set of data, as the oscillator power is varied by attenuation. The gain is the relative power of the amplified output with respect to the throughput of the oscillator without amplification. The extracted power is the difference between the amplified output and the throughput of the oscillator without amplification.

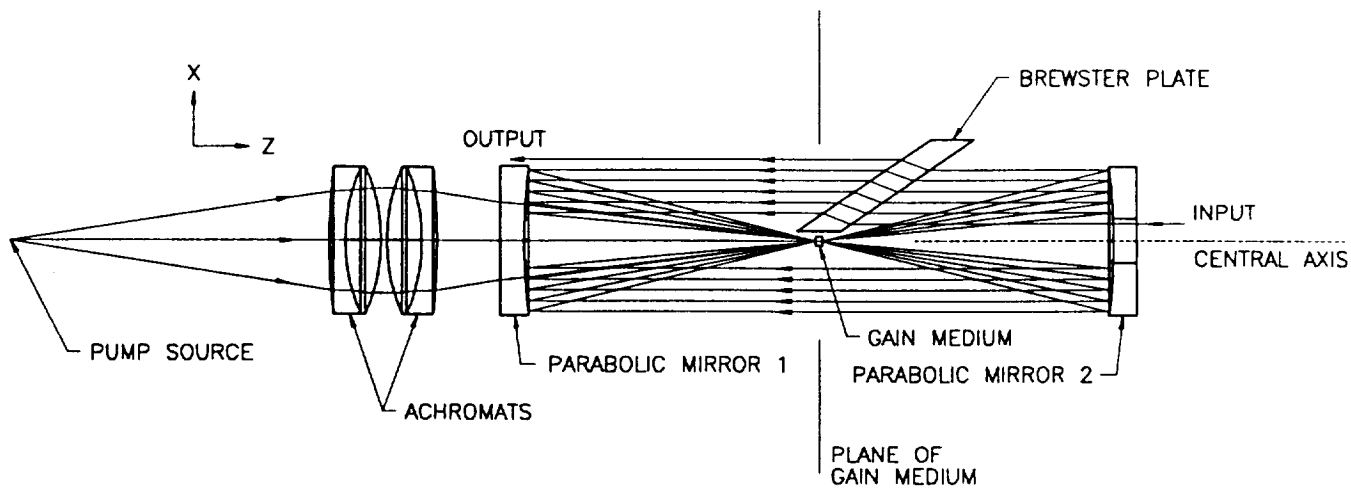
Tables and Table Captions

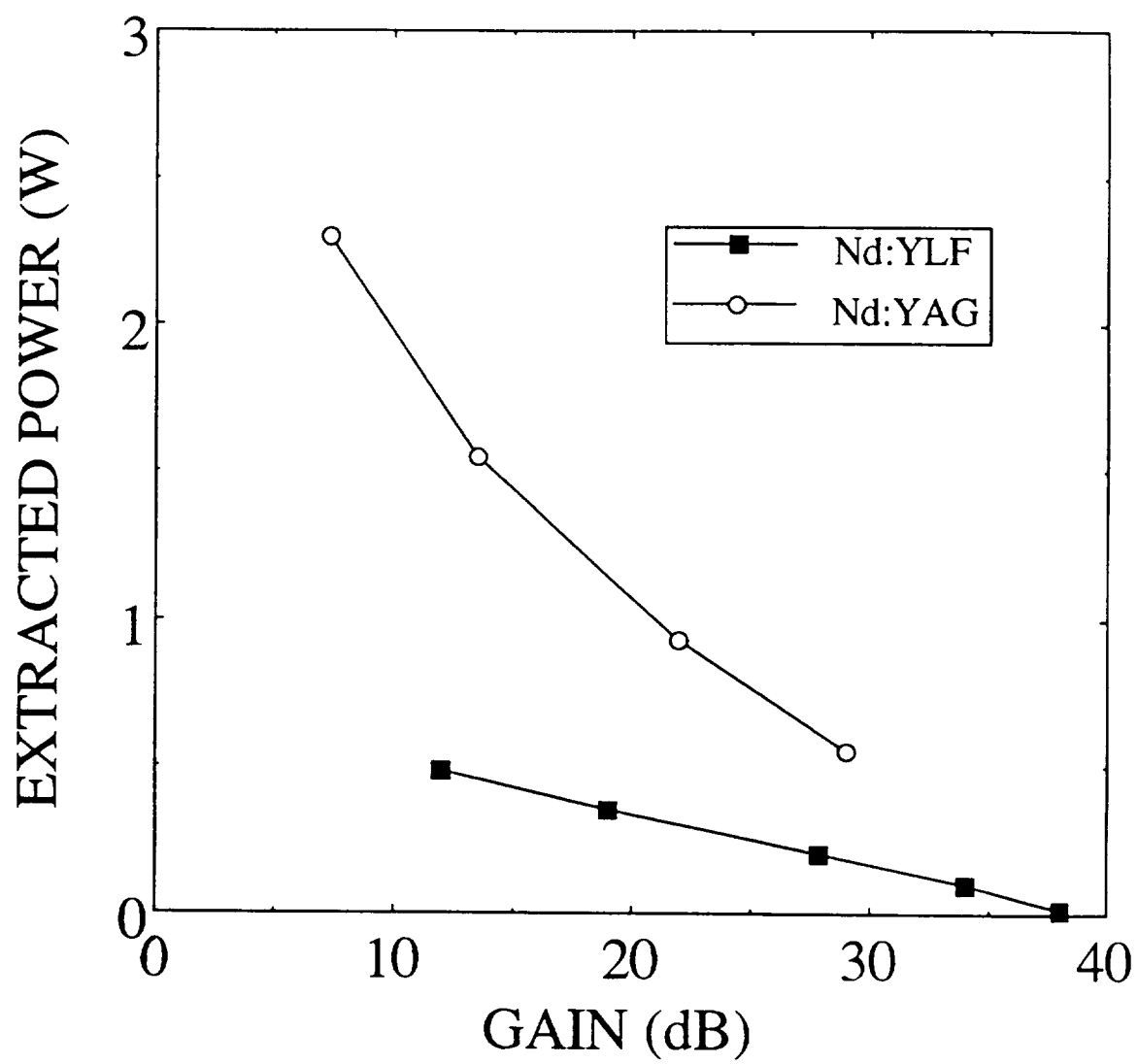
Table 1. CW and pulsed oscillators are single transverse mode diode-pumped lasers. The pulse width of the Q-switched Nd:YVO₄ oscillator increases and the pulse energy decreases with repetition rate as discussed in Ref. 11.

Oscillators	Nd:YLF	Nd:YAG	Nd:YVO ₄
Mode	multi-longitudinal CW	single longitudinal CW	multi-longitudinal pulsed
Max. average power	0.04 W	0.7 W	0.3 W
Wavelength	1.047 μm	1.064 μm	1.064 μm

Table 2. Amplifier results and characteristics. Oscillator material is shown in parenthesis; all data is for the amplifiers. The results are CW. The pump numerical aperture (N. A.) is specified both for in and for out of the plane of the amplifier beam paths. The pump mode diameter is the minimum diameter in the gain material. The available and measured powers refer to the amplifier output.

Amp. Gain Material (Oscillator)	Nd:YLF (Nd:YLF)	Nd:YAG (Nd:YAG)	Nd:YVO ₄ (Nd:YAG)
Material length	3.5 mm	7.5 mm	4 mm
Nd doping	1.45%	1.1%	1.0%
Pump power	1.6 W	13 W	13 W
Pumped Mode	200 μ m diameter	400 μ m diameter	400 μ m diameter
Pump beam N.A.			
in the plane	0.25	0.25	0.25
out of the plane	~ 0.04	0.25	0.25
Small-signal gain	38 dB	38 dB	57 dB
Available power	0.75 W	4.3 W	5.0 W
Measured power	0.64 W	3.2 W	4.3 W





Price List

Laser Products and Accessories
Page 1

Q-Switched Laser Products

Series 110 A-O Q-Switched Laser Products

comprise a laser head, laser head personality module, and controller/power supply with integrated rf driver. Special high power, short pulse or long pulse versions are available. Please call Lightwave for information.

Model 110-03 Nd:YAG Laser @ 1064 nm
.....\$25,650

Model 110-04 Nd:YLF Laser @ 1047 nm
.....\$25,650

Model 110-04-027 Nd:YLF Laser optimized for high
repetition rate operation @ 1047 nm
.....\$28,650

Model 110-04-023 Nd:YLF Laser @ 1321 nm
.....\$28,650

Series 111 A-O Q-Switched Laser Products

comprise a single laser module with integrated control electronics and rf driver. User supplied dc power and trigger signals are required for operation.

Model 111-1047 Nd:YLF Laser
.....\$19,650

Model 111-1321 Nd:YLF Laser
.....\$19,650

Model 111-1064V Nd:YVO₄ Laser
.....\$21,650

Model 111-1342V Nd:YVO₄ Laser
.....\$21,650

Series 111D A-O Q-Switched Laser Products

comprise a laser module with integrated control electronics and rf driver. Includes a development power supply which is necessary to provide dc power and trigger signals.

Model 111D-1047 Nd:YLF Laser
.....\$21,150

Model 111D-1321 Nd:YLF Laser
.....\$21,150

Model 111D-1064V Nd:YVO₄ Laser
.....\$23,150

Model 111D-1342V Nd:YVO₄ Laser
.....\$23,150

Section 4.

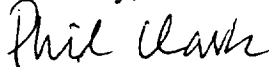
Appendix E. Mailer to 1993 CLEO show visitors regarding amplifier

May 13, 1993

To Our Valued Customer:

Thank you for your interest in The Lightwave Model 160 Optical Amplifier as shown at CLEO '93. Enclosed is preliminary information on the amplifier and some possible configurations with various Lightwave seed lasers. We will only offer the Model 160 amplifier for use with a Lightwave seed laser. Price is expected to be about \$75,000. This does not include the price of the seed laser but does include integration and characterization of the amplifier with the seed laser by Lightwave. Delivery is expected to be in the 6-9 month time frame. It is Lightwave's plan to assist you in your systems application by providing a seed laser/amplifier system optimized for you. Please call us with your specific requirements and we will be happy to work with you.

Sincerely,



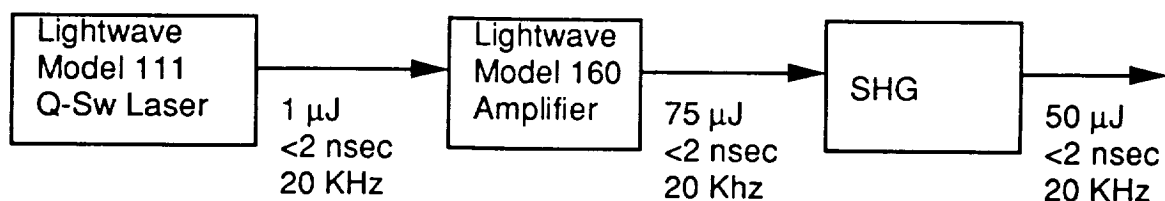
Phil Clark
Sales Manager

MODEL 160 OPTICAL AMPLIFIER

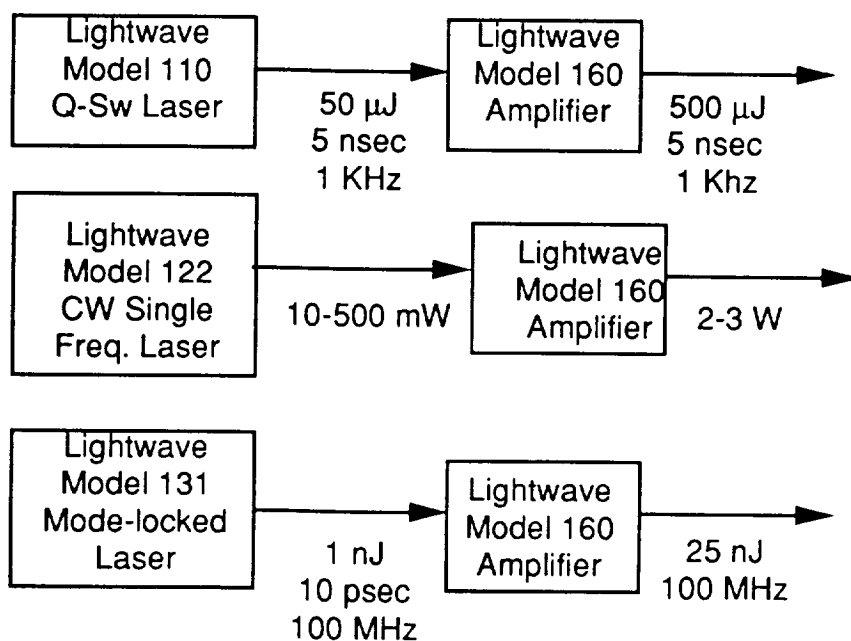
PRELIMINARY PERFORMANCE DATA:

Nd:YAG, Nd:YLF, Nd:YVO₄
Up to 40 dB Small Signal Gain
2-3 Watts Saturated Power
< 1 KW Electrical Input Power

CONFIGURATION AS DISPLAYED AT CLEO '93:



OTHER POSSIBLE CONFIGURATIONS:



A PennWell Publication

Laser Focus World

June 1993

GLOBAL ELECTRO-OPTIC TECHNOLOGY AND MARKETS

- Excimer lasers
for industry
- Back to Basics:
Ruby lasers



LASER

I N D U S T R Y R E P O R T

New products highlight CLEO '93

A host of new laser products were exhibited at CLEO '93 last month, demonstrating once again the show's significance for launching products into the marketplace. Here is a sampler from the CLEO marquee:

American Laser Corp. (Salt Lake City, UT) introduced the LS 1000 argon/krypton-laser system with CW 75-mW output power and 457- to 677-nm wavelengths. Coherent Laser Group (Santa Clara, CA) exhibited the Innova 300 FReD ion-laser system, producing a CW second-harmonic-generated output with wavelengths from 229 to 264 nm. Continuum (Santa Clara, CA) launched the Surelite II, a Q-switched Nd:YAG laser with a double-pulse option, primarily designed for the particle-image-velocimetry market. Lightwave Electronics Corp. (Mountain View, CA) introduced the Series 160 diode-pumped laser/amplifier systems. Lumonics Inc. (Kanata, Ontario, Canada) showed a new look with the PulseMaster 800, a range of excimer lasers featuring total metal-ceramic construction, longer gas lifetime, and reduced operating costs. Micracor Inc. (Acton, MA) featured its Micralase tunable semiconductor lasers with wavelengths ranging from 650 to 860, 1320, and 1550 nm and CW output power from 5 to 25 mW. Spectra Diode Labs (San Jose, CA) introduced a 3-W CW visible (680 nm) fiber-coupled laser diode.



Report Documentation Page

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5. Supplementary Notes			
5. Abstract The overall objective of this Phase II effort was to develop and deliver to NASA a high repetition rate laser-diode-pumped solid-state pulsed laser system with output in the green portion of the spectrum. The laser is for use in data communications, and high efficiency, short pulses, and low timing jitter are important features. We developed a short-pulse 1 μm laser oscillator, an new multi-pass amplifier to boost the infrared power, and a frequency doubler to take the amplified infrared pulsed laser light into the green. this produced 1.5 W of light in the visible at a pulse repetition rate of 20 kHz in the laboratory. The pulses have a full-width at half maximum of near 1 ns. We are commercializing the results of this program.			
7. Key Words (Suggested by Author(s)) laser-diode-pumped Solid-state laser pulsed laser Optical amplifier laser		18. Distribution Statement unclassified/unlimited	
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High Gain Diode CW-Pumped Solid-state Optical Amplifier

Henry Plaessmann, Joseph J. Alonis, Sean A. Re, David L. Vecht, William Grossman

Figure Captions

Fig. 1. Amplifier consists of 2 parabolic mirrors ($f = 4"$, $\phi = 2"$) in a confocal configuration. The gain medium is at the center. The glass plate inserted at Brewster's angle as shown creates the multi-pass geometry. Light is input through a center hole in one of the parabolic mirrors.

Fig. 2. Plots of extracted power and optical-to-optical conversion efficiency as functions of pump power. In this case, 500 mW from a cw single-frequency Nd:YAG ring laser is amplified in Nd:YVO₄ pumped by up to 6 W in a 400 μm mode. Note the slight decline in conversion efficiency with increasing pump power once saturation is reached--this is due to the increased heating of the gain region which diminishes the spectral overlap between the YAG oscillator and YVO₄ amplifier.

Sub-nanosecond Pulse Generation from Diode Pumped Acousto-optically Q-switched Solid-state Lasers

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December 31, 1992

Abstract

Miniature diode-pumped acousto-optically Q-switched solid-state lasers deliver pulse durations as short as 600 ps at wavelengths near 1 μm . Specifically, Nd:YVO₄ lasers operating at 1.064 μm produce 600 ps/5 kW pulses at 1 kHz, 1.0 ns/2 kW pulses at 20 kHz, and 1.9 ns/0.5 kW pulses at 100 kHz. A Nd:YLF laser at 1.047 μm generates 700 ps/15 kW pulses at 1 kHz, and 1.2 ns/4 kW pulses at 10 kHz. At 1.342 μm , a Nd:YVO₄ laser produces 3.3 ns/0.8-0.6 kW pulses at 1-10 kHz.

A deep-space communications application known as pulse position modulation (PPM)¹ requires short duration, high power, high repetition rate pulses, and NASA's need for a laser transmitter for experiments in this field is the primary motivation for the laser oscillator development project described herein.² Other applications such as range finding, regenerative amplification, fiber optic sensing, and nonlinear optics also benefit from short pulses. Since the introduction of semiconductor laser pumping of solid-state lasers in 1968³ and, subsequently, the Q-switching of such devices in 1982⁴, rapid progress has been made in increasing output power and repetition frequency and reducing pulse width.⁵⁻⁹ A diode-pumped, electro-optically Q-switched fiber laser produces 2 ns, >1 kW, 1.053 μm pulses at frequencies up to 1 kHz.¹⁰ Also electro-optically Q-switched, a microchip laser pumped by a diode laser generates 300 ps, 25 kW, 1.064 μm pulses at a 5 kHz repetition rate.¹¹

Generating such pulses from a Q-switched laser requires high gain and a resonator design that yields a short cavity lifetime. This paper presents miniature, diode-pumped, acousto-optically Q-switched Nd:YLF¹² and Nd:YVO₄¹³⁻¹⁶ lasers operating at 1.047 μm and 1.064 or 1.342 μm respectively. The devices utilize an extremely short resonator to minimize cavity lifetime and laser crystal cooling to achieve high gain⁹ and pulses as short as 600 ps at 1.064 μm .

Table 1 describes the four lasers tested, and Figure 1 is a sketch of the Nd:YVO₄ lasers. The crystal length is 2.3 mm. The first surface is flat, and coated to be highly reflective (HR) at the lasing wavelength and highly transmissive (HT) for pump light--see Table 1. The second crystal surface is also flat, but is uncoated and oriented at

Brewster's angle. For π wavelength selection the crystal axis is oriented as shown. Active laser crystal cooling is accomplished by mounting the gain medium on a thermoelectric cooler, and a thermistor feedback circuit is used for temperature regulation (-10 to 0 °C). A TeO₂ Q-switch is central to the resonator, and it is 3.2 mm long with both flat surfaces uncoated and at Brewster's angle. The switch has a maximum RF input power rating of 2 W at a frequency of 108 MHz. Using a fast photodiode and a tightly focussed He-Ne laser to probe the acousto-optic aperture yields a switching speed of 6 ns; however, the calculated acoustic transit time across the laser mode limits switching speed to approximately 18 ns. The last resonator component is a 0.7 mm long fused silica output coupler. Its first surface is uncoated and at Brewster's angle, and the second has a 15 mm radius of curvature and is coated for transmissions given in Table 1. In the Nd:YVO₄ lasers there is a bend in the resonator axis of approximately 20° due to the large refractive index difference between the laser crystal and the output coupler. The three components are separated by minimal air gaps, and the overall cavity length is about 7 mm. The radii of the apparent TEM₀₀ beam waists located at the first Nd:YVO₄ surface are given in Table 1. This resonator geometry has low internal losses, a minimum number of coated surfaces, and an extremely short cavity lifetime.

The Nd:YLF laser resonator configuration is virtually identical to that for Nd:YVO₄ except for the resonator parameters listed in Table 1. Also, the resonator axis is straight (no bend).

Each resonator is pumped by a laser diode with a 1 x 50 μm emitting area (Sony model 322V). For Nd:YVO₄ the diode wavelength is temperature tuned to the 0.808 μm

absorption band with an output power of 430 mW, and for Nd:YLF it is adjusted to 0.798 μm with 400 mW output. Pump light is focussed to a $80 \times 80 \mu\text{m}$ approximately square spot in the laser crystal. Diode laser polarization is oriented parallel to the laser crystal axis as shown in the diagram.

Pulse width measurements in the sub-nanosecond regime are difficult. For laser #1, pulse durations are measured as follows: the output pulse is split with a 50/50 beamsplitter; the reflected light is directed to a fast photodiode; the photodiode output triggers a sampling oscilloscope; the light transmitted by the beamsplitter is severely attenuated and launched into a 60 foot length of single-mode fiber; the fiber output is incident on a RCA 30617E InGaAs photodiode and input to the sampling scope via 3 feet of RG-58 coaxial cable. By triggering the oscilloscope with a portion of the optical pulse, timing jitter is eliminated from the measurement. The single-mode fiber is used to achieve the trigger-to-signal delay required by the sampling scope without introducing pulse broadening, and attenuation prior to fiber coupling is necessary to prevent stimulated Raman scattering.¹⁷ Dispersion in 60 feet of single-mode fiber is negligible. The combined impulse response of the RCA photodiode, 3 feet of RG-58 cable, and the sampling oscilloscope is 260 ps as measured with a < 10 ps mode-locked Nd:YLF laser incident. For lasers #2, #3, and #4 pulse widths are measured with a New Focus 1 GHz photoreceiver connected to a 400 MHz oscilloscope by 3 feet of RG-58 cable (impulse response ≈ 1 ns), and then deconvolved; the deconvolution is verified by measuring the pulses emitted from laser #1 on this setup and comparing the results to those from the above sampling scope measurement system.

Pulse width (FWHM) and pulse energy as functions of repetition frequency are plotted in Figures 2 & 3. The shortest pulse widths are achieved by laser #1 at low repetition rates. At 1 kHz this laser delivers 3 μ J pulses of 600 ps duration (see pulse trace--figure 4), and ≤ 1 ns, ≥ 2 μ J performance is maintained at frequencies up to 20 kHz. With a change of output coupling to 25%, laser #2 generates ≤ 1.9 ns pulses at ≤ 100 kHz; however, repetition rates are limited to ≥ 50 kHz because the RF power necessary to hold-off pulses below this frequency exceeds the maximum input power rating of the Q-switch. Laser #1 is not repetition rate limited; however, hold-off and/or switching speed problems arise at low repetition rates with either a reduction in coupling or an increase in pump power. This laser operates at only twice threshold while theory predicts the shortest pulses to be generated at approximately 3.5 times threshold, so improvements in Q-switch design are required if even shorter pulses are to be achieved in the low repetition frequency regime. After-pulsing, a phenomenon where a secondary, smaller pulse is emitted some time after the primary pulse, is not observed in lasers #1 and #2.

From laser #4 pulses as short as 700 ps with almost 11 μ J energy are generated at a 1 kHz repetition frequency, but in this laser sub-ns performance is limited to rates of about 5 kHz and less. Above 5 kHz pulse durations grow to approximately 11 ns at 100 kHz where energies drop to < 1 μ J. After-pulsing is observed in the YLF laser, and the device is not repetition rate/hold-off limited.

Although the performance of laser #3 does not approach the sub-nanosecond pulse durations of lasers #1 and #4, significant improvements over previously published results⁸⁻⁹ near 1.3 μ m are achieved. By simply altering the resonator parameters to those

listed for laser #3 in Table 1, pulses of 3.3 ns duration are generated from 1-10 kHz while pulse energy varies from about 2.6 to 2.1 μJ over the same repetition frequency range. At rates as high as 100 kHz pulse widths are still only 14.0 ns, though energy is down to 0.5 μJ . In this case, diode laser pump power is 400 mW.

Continuous wave operation of laser #1 yields 54 mW at full pump power with a threshold pump power of approximately 225 mW. The output coupler clearly dominates the cavity losses, so at the maximum pump power of 430 mW the pumping rate is 1.9 times that at the lasing threshold, and the computed unsaturated double pass gain is 9 dB. For laser #2 cw threshold is reached with 55 mW of pump, maximum power output is 87 mW with 400 mW of pump light (7.3 times threshold), and gain is also 9 dB. Experimental error most likely accounts for gain calculations producing the same result at two slightly different pumping rates. Laser #3 emits 46 mW of cw power and attains threshold with a pump power of 80 mW, indicating an unsaturated double pass gain of 1.7 dB. Laser #4 achieves threshold with a pump power of 72 mW, and pumping with 400 mW (5.6 times threshold) delivers 71 mW of cw output. Gain in this case is 7 dB.

Second harmonic generation is an important application of Q-switched lasers. When confocally focussed in a 5 mm long KTP crystal laser #1 generates approximately 0.9 mW average second harmonic power at 1 kHz and 7.7 mW of green light at 10 kHz. Conversion efficiency is 37% for the repetition frequency range of 1 to 10 kHz.

Short pulsed solid-state lasers are useful for fiber optic applications such as optical time domain reflectometry. Coupling Laser #1 to a 300 m length of single-mode fiber results in pulse shape distortion due to feedback to the oscillator. Since the laser's linear

polarization is lost in the fiber anyway, a $\frac{1}{4}$ -waveplate is inserted prior to the coupling lens to act as a crude isolator, and first surface feedback is effectively eliminated. By passing the transmitted fiber output through a single grating monochromator, the first four Stokes orders of stimulated Raman scattering are resolved.¹⁷ Energy is depleted from the fundamental $1.064\text{ }\mu\text{m}$ pulse and shifted to wavelengths of 1.12 , 1.18 , 1.24 , and $1.32\text{ }\mu\text{m}$, and the scattered pulse intensity and duration decrease with increasing Stokes order. No anti-Stokes shifts are observed in this experiment.

In conclusion, sub-nanosecond diode-pumped acousto-optically Q-switched solid-state lasers operating at wavelengths near $1\text{ }\mu\text{m}$ and $1.3\text{ }\mu\text{m}$ are developed and characterized. High performance is achieved with both Nd:YLF and Nd:YVO₄ though the latter exhibits greater gain, slightly shorter pulse durations at low repetition rates, and at $1\text{ }\mu\text{m}$ maintains sub-nanosecond widths at repetition frequencies up to 20 kHz . Besides materials, key design aspects are the miniature resonator configuration and especially the TeO₂ Q-switch. TeO₂ is a superb acousto-optic crystal for Q-switches because of its high figure of merit and good damage properties. That a small TeO₂ Q-switch has sufficient speed and loss modulation to generate sub-nanosecond pulse durations is a significant result of these experiments. Without a high performance switch there is little hope of producing such short pulses from an acousto-optically Q-switched laser. To our knowledge, these are the first reports of sub-nanosecond pulse durations generated by acousto-optically Q-switched lasers and of Nd:YVO₄ producing Q-switched pulses at $1.3\text{ }\mu\text{m}$. Furthermore, the high repetition rate (100 kHz) $1\text{ }\mu\text{m}$ pulse width and the $1.3\text{ }\mu\text{m}$ pulse durations are the shortest ever reported for any Q-switching mechanism or laser

material. In addition to described wavelengths, this laser design is suitable for generating short pulses at the 1.053, 1.313, and 1.321 μm lines of Nd:YLF. It is adaptable to other solid-state laser crystals such as Nd, Er, or Tm doped YAG.

Special thanks to the National Aeronautics and Space Administration and its Jet Propulsion Laboratory for supporting this project (contract NAS7-1145).

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<u>Laser</u>	<u>#1</u>	<u>#2</u>	<u>#3</u>	<u>#4</u>
Material	Nd:YVO ₄	Nd:YVO ₄	Nd:YVO ₄	Nd:YLF
Doping[%]	1.5	1.5	1.5	1.45
Wavelength[μm]	1.064	1.064	1.342	1.047
Waist[μm]	44	44	50	41
Coupling[%]	65	25	7.5	25

